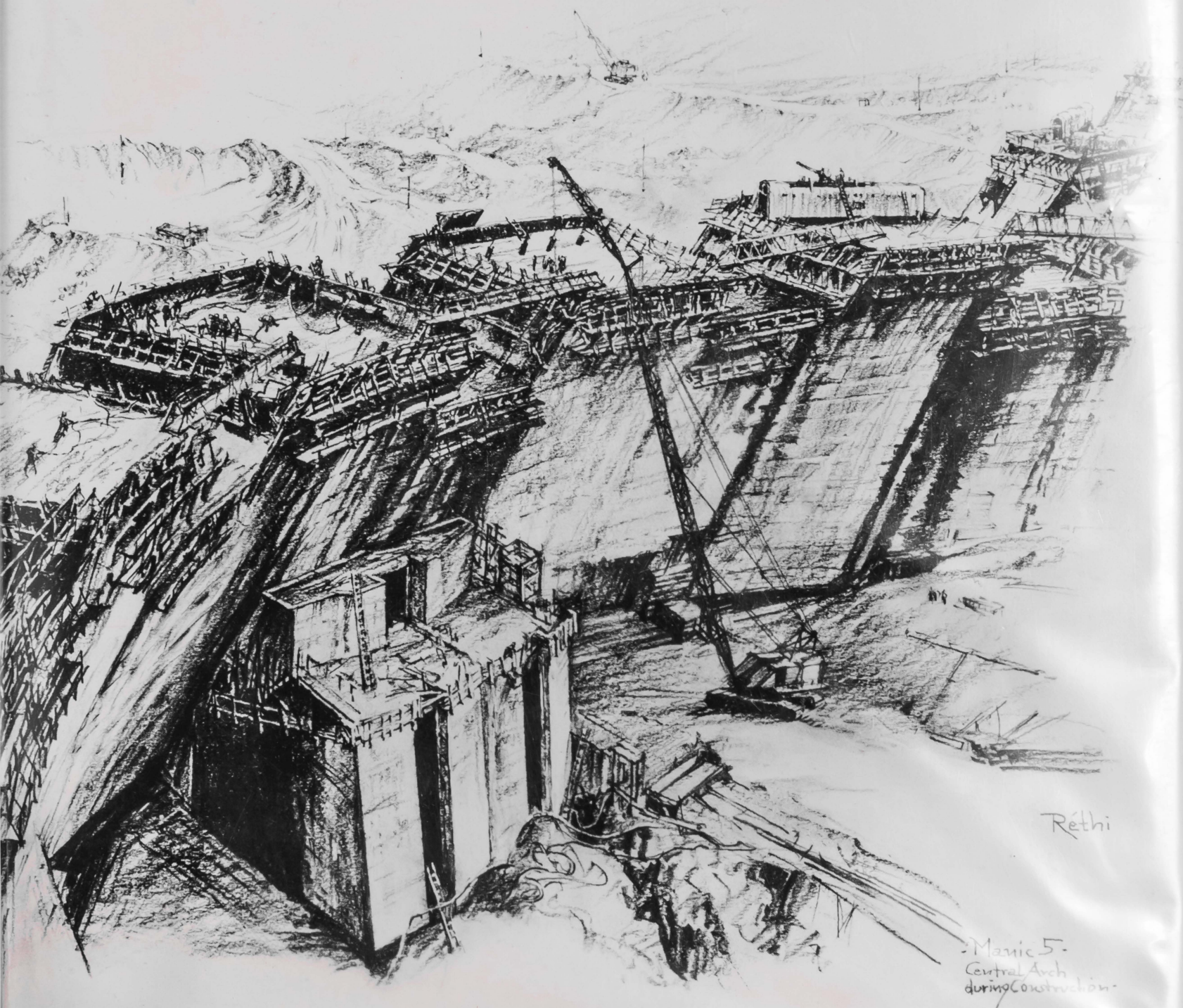


MANIC 5

The building of the Daniel Johnson Dam

Lili Réthi and William W. Jacobus



Manic 5.
Central Arch
during Construction.

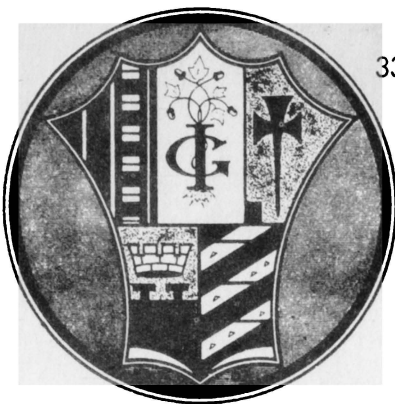
MANIC 5

Lili Réthi and William W. Jacobus

It is 703 feet high at its center arch, 4,310 feet long, and weighs approximately 6,000,000 tons. Building it required the services of over 3500 workers, and consumed 15,000,000 bags of cement, 1,700,000 tons of sand, 2,500,000 tons of rock, 72,000,000 gallons of water. The world's biggest multiple arch dam, it is a dramatic part of Canada's mighty Manicouagan-Outardes Rivers hydroelectric project. Originally called Manic 5, it was officially renamed Daniel Johnson Dam in honor of Quebec's late Prime Minister.

This is the story of the building of that dam. The drama, the beauty, and the awesome magnitude of the undertaking are captured in these pages in sixty-four drawings by Lili Réthi, an artist whose work, said *The Christian Science Monitor*, "pleases the technically trained man but at the same time holds the full romance of engineering in its grasp." The narrative by William W. Jacobus, Jr. complements the picture story with facts and figures, and sometimes the emotions, involved in one of history's most complex engi-

(continued on back flap)



Goodwyn Institute Library
33 South Front Street • Memphis, Tennessee

BUSINESS • TRADE • INDUSTRY
ENGINEERING • ARCHITECTURE
SCIENCE • CHEMISTRY • PHYSICS
LOCAL HISTORY

Sci
627.820971
R438

7112811

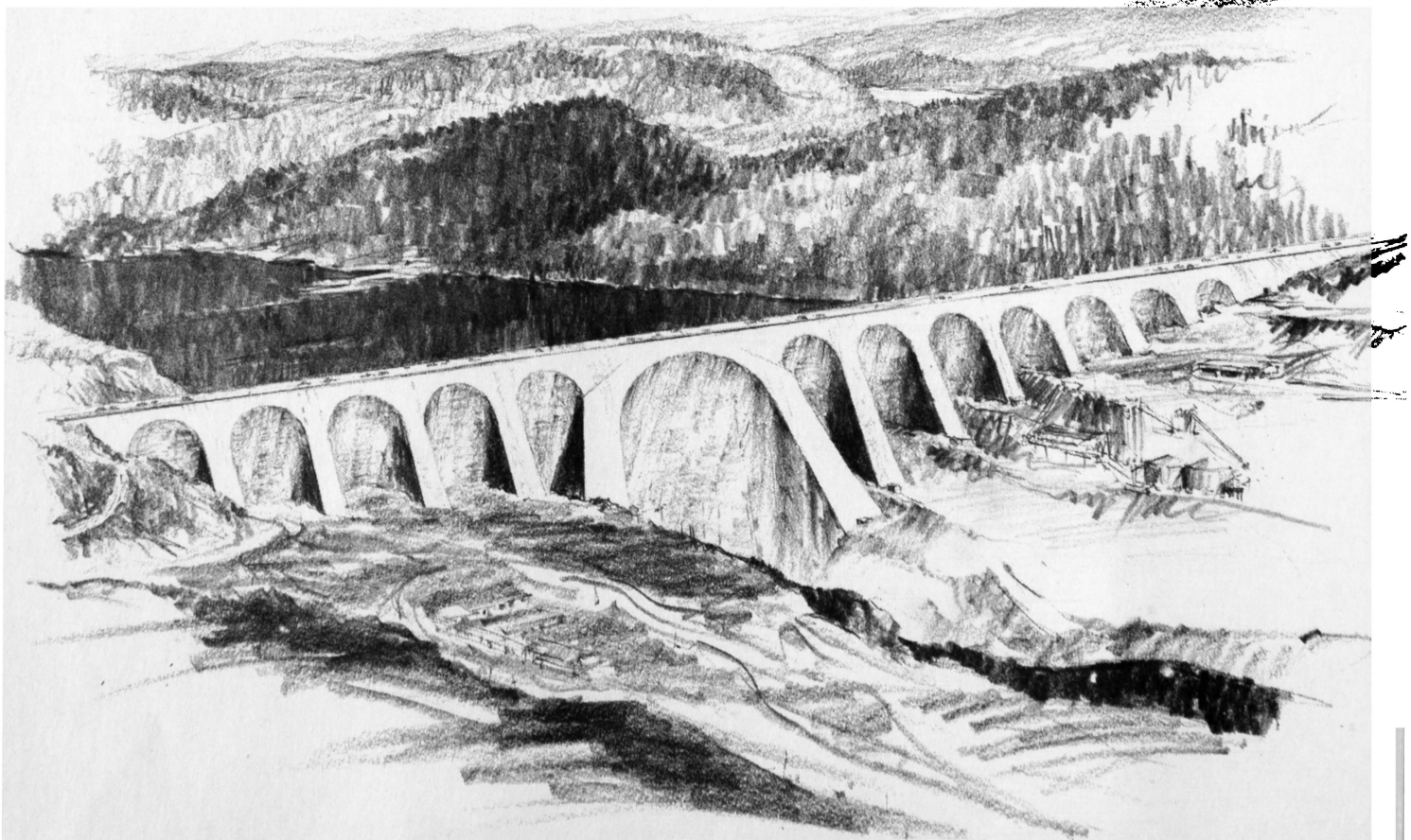
NO LONGER THE PROPERTY
OF MEMPHIS-SHELBY COUNTY
PUBLIC LIBRARY INFORMATION CENTER

Bus-Tech

MEMPHIS PUBLIC LIBRARY
SHELBY COUNTY LIBRARIES

For the Residents
of
Memphis and Shelby County

MANIC 5



MANIC 5

THE BUILDING OF THE DANIEL JOHNSON DAM

by **Lili Réthi, F.R.S.A.**

and **William W. Jacobus, Jr.**

**Foreword by the Honorable Robert Bourassa, M.P.P.
Prime Minister of the Province of Quebec**

**DOUBLEDAY & COMPANY, INC., GARDEN CITY, NEW YORK
1971**

LIBRARY OF CONGRESS CATALOG CARD NUMBER 69-20080

ILLUSTRATIONS COPYRIGHT © 1971 BY DOUBLEDAY & COMPANY, INC.

TEXT COPYRIGHT © 1971 BY WILLIAM W. JACOBUS, JR.

ALL RIGHTS RESERVED

PRINTED IN THE UNITED STATES OF AMERICA

FIRST EDITION

7112811
MEMPHIS AND SHELBY COUNTY
PUBLIC LIBRARY

*To Lili Réthi—
for whom a dam became a work of art.*

FOREWORD

For all Quebecers, Manic 5 has become a symbol, the proof of our ability to meet the challenge of science and technology. Manic 5 is an achievement by all Quebecers, the result of a joint effort by the state, private enterprise, professionals, technicians and workers. Manic 5 reflects the image of today's Quebec: dynamic, daring, demanding and fascinating.

Manic 5: The Building of the Daniel Johnson Dam by Lili Réthi and William W. Jacobus, Jr., is the living and authentic story of that gigantic technical and human realization. In a way it is also a tribute of admiration to the courage and determination of all those who were working hand in hand to give Quebec its new dimension.

ROBERT BOURASSA
*Prime Minister of the
Province of Quebec*

MANIC 5

■ When Jacques Cartier first sailed up the St. Lawrence River in 1534, he undoubtedly marveled at the giant stream while not really knowing how important a discovery he had made. He did not know that it was the overflow drain of five huge lakes in the center of a continent. There were many tributary streams flowing southward into the St. Lawrence, but most of these were raging torrents, snow-melt water crashing over cataracts and rapids, forbidding avenues for the waterborne traveler.

Cartier claimed the new land for France and returned several years later to establish the first settlement on the St. Lawrence, but the small colony lasted only through the winter of 1541-42. For the next fifty years, France paid little attention to its New World colony, leaving it to the Indians who had come there long before the white man.

It was not until 1608 that Samuel de Champlain founded Quebec, the first permanent settlement in Canada. But in the interim, French fishermen worked the rich fishing grounds off the coast of Newfoundland and the eastern mainland. They began fur trading with the Indians when they came ashore to dry their catches. By the early 1600s fur trading had become the colony's major business enterprise.

As the explorers continued westward, the fur trading companies moved in and, until about 1660, completely controlled and all but owned what was then Canada. It is fairly certain that the first white men to set eyes on many of the St. Lawrence's tributaries were fur traders.

Three hundred years later, the Hydro Electric Commission of the Province of Quebec turned to a pair of these tributaries, the Manicouagan and the Outardes rivers, for electric power. The two rivers flow nearly parallel to each other, joining the St. Lawrence about 250 miles downstream from Quebec City, roughly opposite the shank of the Gaspé peninsula. The Manicouagan drains a 17,600-square-mile watershed and falls 1900 feet in its 350-mile journey south. The Outardes drains 7258 square miles, falling 1800 feet in about 270 miles.

After many years of study and planning, Hydro-Quebec launched a vast construction program, spending nearly \$2 billion on seven hydroelectric proj-

ects, three on the Outardes, four on the Manicouagan, that would harness the two rivers' full hydroelectric potential of nearly 7.5 million horsepower, enough horsepower to generate 31.5 billion kilowatt-hours of electricity annually.

Spectacular as the over-all development was, one phase, one of the seven projects, stole the limelight from the very beginning. About 125 miles up the Manicouagan River, Hydro-Quebec engineers set out to build a record-setting structure—the world's highest multiple-arch concrete dam—which would have a central arch 703 feet high, taller than any of Montreal's skyscrapers. Since it was to have been the fifth dam on the Manicouagan River in the early planning stages, the dam was rather unimaginatively named "Manicouagan 5," which quickly became "Manic 5."

The Indians had named the river "Manikuagan"—"the spring where thirst is quenched"—and the early cartographers used this name on the first maps. Just to the west of the Manikuagan, the maps showed the Rivière aux Outardes, French for the "river of the wild geese." Today, it is the "Outardes" and the "Manicouagan." The spellings are not important, but the rivers are.

By the turn of the twentieth century, only twenty-two years after the first electric arc lights illuminated the streets of Montreal, Canada's Commission on Conservation resourcefully had explored and recorded the vast potential of the two rivers, as a source both of hydroelectric power and pulp wood. There is, in fact, an interesting historical relationship between the pulp mills and the advent of hydroelectric power.

Although the hydraulic turbine was invented in the early 1800s, most electric generators, then called "dynamotors," were driven by steam engines. Quebec's pulp- and sawmill operators were quick to see the advantages of electric lights in their mills. They had no turbine, as such, but with typical bush-country ingenuity, they soon harnessed their big water wheels to the new dynamotors, creating some of the world's first hydroelectric plants.

As early as 1911 the Commission on Conservation quite accurately described the Manicouagan and Outardes rivers. The commission charted the waterfalls, rapids, and giant cascades traced by the two rivers as they tumble south over the heavily glaciated topography of the Laurentian Plateau. Engineers and geologists pinpointed the best sites for hydroelectric developments, and noted: "There is an abundance of cordwood. According to official explorers, two cords per acre could be obtained." And, of course, the raging water with its great potential to make electricity would also carry logs to the pulp mills down on the St. Lawrence. The electricity not only could light the mills, but if properly harnessed, could drive the machinery.

But these early engineers were conservative. With their limited knowledge and technology, they could not begin to conceive of the rivers' tre-

mendous potential—7.5 million horsepower that today can drive generators with a capacity of 5.6 million kilowatts. Even if these men had been aware of all these potential kilowatts, they never could have foreseen a demand for so much power. At the end of World War I, the Province of Quebec had harnessed about 500,000 horsepower with hydroelectric plants. By 1940 the province could boast 3.5 million horsepower of hydro power, and government officials in 1955 were reconciled to having to double Quebec's power capacity every decade. Total installed capacity had soared to 15 million horsepower by 1964, nearly half the total hydro capacity of Canada. This ravenous demand for power had to be met.

Because of it, Quebec's engineers retraced the steps of the "official

Before full-scale construction can begin on the dam, Hydro-Quebec has to build a self-contained city in the wilderness of Quebec's bush country.



explorers" to harness the two rivers. Quebec, Canada's oldest and biggest province, embarked on a daring adventure in engineering and construction. The world engineering fraternity was abuzz from the start, during construction and after. Engineers came from all over the world to watch Quebec build Manic 5. The giant, thin concrete arch, leaning on massive buttresses and assisted by twelve smaller arches on its flanks, would have to shut off the mighty Manicouagan for eight years, the time it would take to fill the reservoir and submerge 750 square miles of land. By raising the level of two big lakes upstream, Manic 5 would create the sixth largest reservoir in the world with a volume of 115 million acre-feet, 1 acre-foot being the volume of water required to cover an acre of land 1 foot deep, that is, 325,851 gallons.

The watershed of the Manicouagan was unusually advantageous for construction of such a large man-made lake. Aerial surveys revealed that 64 per cent of the drainage basin's more than 17,000 square miles was upstream of the river's most important waterfalls. Within this section of the watershed were two big lakes, one named not surprisingly Lac Manicouagan, the other Lac Mushalagan. These two natural lakes covered a large area already, and the possibility of building a huge artificial lake, which would be more than 1000 feet higher than the river's outlet elevation, was immediately apparent to engineers studying the aerial contour maps. The key to impounding such a reservoir was finding a suitable site on the river where a dam could be built. This dam and its vast reservoir were of prime importance to development of the entire river.

The very nature of the Manicouagan River and the climate of the bush country must be understood in order to appreciate the importance of the big upstream storage reservoir. The weather in this forbidding part of the world is harsh, at best. "We have two seasons here," quips the seasoned veteran of the bush country, "winter and July." The mercury dives to 60 below zero Fahrenheit some winters—and winter begins about mid-September. Snow flurries come as early as August, as late as May. Snowfall averages 156 inches per year.

In many ways the land freezes into total dormancy. Beautiful little waterfalls, spilling over towering cliffs, freeze solid, clinging like long white beards to the cold granite. As tributary streams turn to ice, the flows in rivers begin to dwindle, and by the dead of winter even the mighty Manicouagan and Outardes rivers become mere trickles compared to their summer torrents. Hydrologists call these rivers "flashy"—in many sections of the Manicouagan variations as great as 45 feet between high and low levels could be found. The normal spring flood at the mouth of the river was about 200,000 cubic feet per second, while winter low flow ebbed to 8000 cubic feet per second.

In order to harness the full hydroelectric potential of a river like the Manicouagan, this wide variation in flows had to be eliminated. The giant turbines could not stand idle half the year. Thus, Hydro-Quebec's engineers were fascinated with the possibilities of the upper Manicouagan. The big reservoir envisioned would not only supply a large powerhouse at the impounding dam, but would create a dependable year-round flow in the river for a series of downstream dams and powerhouses built like a stairway down to the St. Lawrence.

It was 1955 when Hydro-Quebec decided it was time thoroughly to investigate the Manicouagan and Outardes rivers. Looking twenty years ahead, the commission realized that Quebec's voracious demand for power called for a development of unprecedented proportions. Two engineering firms, H. G. Acres Company Limited, of Niagara Falls, Ontario, and Surveyer, Nenniger & Chênevert, of Montreal, were retained jointly to prepare a report on the Manicouagan's power potential. Surveyors from the two engineering companies first had to go into the bush and accurately record the profile of the river and its principal tributaries—the Mushalagan, Touloustouc, Racine de Bouleau, Thémines, and the Hart Jaune rivers.

To produce a river's profile, surveyors do what is called "leveling." They measure with instruments the river's elevation above sea level at many locations. These measurements are finally plotted on a graph, which has elevation in feet on its vertical axis, distance in miles from the river's mouth on the horizontal axis. The resulting graph is a profile of the river's descent, in some areas sloping gently, dropping abruptly at waterfalls and rapids.

During 1956 the engineers refined their studies, poring over special aerial photographs some of which were photographic contour maps showing the precise topography of the river's course. Geologists interpreted other photographic mosaics and by year's end the consulting engineers had selected twenty-seven possible damsites. Most of these sites were located in the general vicinity of the steep drops on the profile, the waterfalls, and rapids. Additional studies and estimates ultimately eliminated all but eight sites, and during the summers of 1957 and 1958 Acres and SNC survey teams went into the field at these sites for detailed surveys of ground topography, geological inspection, and preliminary core drilling to corroborate the geologists' surface inspection.

Using the results of these investigations, the consultants made preliminary layouts and estimates of what might be built at each of the eight sites. But the sites could not be considered separately—the final development would be a combination of several dams, which, ideally, would harness the river completely. The water in the reservoir farthest downstream should back up as near as possible to the next dam upstream, the second dam's reservoir backing the river up to the third dam, and so on.

Acres and SNC concluded that three dams, one just below Falls No. 2, a second about 5 miles above Falls No. 3, and a third, 1 mile above Falls No. 5, presented the most advantageous combination. Dams at these sites, which came to be known as Manic 2, 3, and 5, permitted the greatest total power output at the lowest cost per horsepower installed. Also, they completely used the total hydraulic head available between the storage reservoir proposed at Manic 5 and a small existing power plant, built in 1953 near the river's mouth by the Manicouagan Power Company.

■ ■ With the preliminary engineering out of the way, the hard part began. Locating a damsite on an aerial map is one thing, but building it in a godforsaken part of the world like this is something else again. The early survey teams returned telling of a summer in a sportsman's paradise—fish that had never seen a hook before, moose and other game in abundance. But they were talking about summer. The dam builders were not going on a fishing trip. They would be at Manic 5 for more than ten years, all year around. The dam, its powerhouse and its tunnels would require 3,350,000 cubic yards of concrete. Almost 400 pounds of cement for each of those cubic yards would have to be brought into the remote site. Huge components, weighing hundreds of tons, for the powerhouse generators and turbines would have to be brought into the bush, more than 100 miles from the nearest town.

The town, called Baie Comeau, was not much of a town either, at that time. Colonel Robert R. McCormick established a paper mill at Baie Comeau in 1935 and began exploiting the Manicouagan River's pulp potential for his *Chicago Tribune* and *New York Daily News*. The roads between Quebec City and Baie Comeau were bad enough. But heading north from Baie Comeau toward the Manic 5 site were only the crudest of logging trails slashed out by McCormick's Quebec North Shore Paper Company.

The dam builders needed a road, and one that could handle heavy truck traffic in all kinds of weather. Engineers estimated that a truckload of cement would leave Baie Comeau's dock on the St. Lawrence every fifteen minutes when dam construction was in full swing. The Manic 5 construction camp would be home for more than 3000 persons and the road would be their primary link with the outside world.

The challenge was awesome, but the ambitious Quebecois knew they could do it. Their engineers and construction men had gone into the bush 5000 strong and built the big Bersimis hydro development in the 1950s. Although somewhat smaller than the Manic-Outardes scheme, and closer to Montreal and Quebec City, Bersimis also was 100 miles from the nearest

town. Three dams, all at least 200 feet high, were built and the Bersimis River was put to work developing more than 1.5 million kilowatts for the power-hungry province.

Bersimis was tough and Manic 5 would be tougher. But the province needed the power by 1975, a conclusion reached by government experts in 1955, and now it was up to the engineers, bulldozer operators, laborers, and all the rest, to go again into the bush, spend years of back-breaking labor, and, finally, to send back to the population centers Quebec's most valuable natural resource—hydroelectric power.

It was the fall of 1959, when the so-called advance party set out from Baie Comeau to carve the initial trail northward to the Manic 5 site. A bush-country advance party is similar to the expeditionary parties familiar in the arctic and antarctic. Conditions in the bush are not quite as harsh as on the icecaps, but they are still far from hospitable.

An advance party in the bush is built around big crawler tractors, the whining, clanking workhorses of construction. The other prime element of an advance party is men. Nor will ordinary men do. They have to be tough, resourceful, experienced construction men. Although they know where they are going, their life on the tractor trail will be only a shade better than that of the early explorers. The advance party is a self contained unit. The big 'dozers not only break trail, pushing over the virgin topography, but they must drag all the party's supplies and equipment as the trail is extended. Since the 'dozers' steel blades cannot do everything, the party takes along air-powered rock drills mounted on skids, big portable air compressors to run the drills, dynamite, chain saws, all kinds of hand tools, fuel for the machines, a small field kitchen, and all the other food and provisions needed for a sojourn into the forest.

The advance party tries to find the best route through swampy bogs, over streams, up hills, and down the other side. As chain saws fell the trees, 'dozers push them to the side or heap them up for burning where the forest is not too dry. Dynamite blasts out stumps that will not succumb to 'dozer blades. When the glacier-worn outcroppings obstruct the route, the party brings up its rock drills, loads the holes with dynamite, and sculpts a hard-rock trail. The trail obviously cannot go over the highest cliffs or the lowest bogs, so the party finds the shortest possible route around these obstacles.

Although the tractor trail to Manic 5 would be rugged, the advance party had to keep in mind that a permanent access road would follow more or less in their tracks. This road would have to handle conventional highway traffic as well as heavy trucks. But the advance party's primary goal was to break through to the gorge where Manic 5 would be built. A construction camp for 3500 workers had to be built and most of the supplies, heavy equipment, and buildings would have to come overland. The advance party

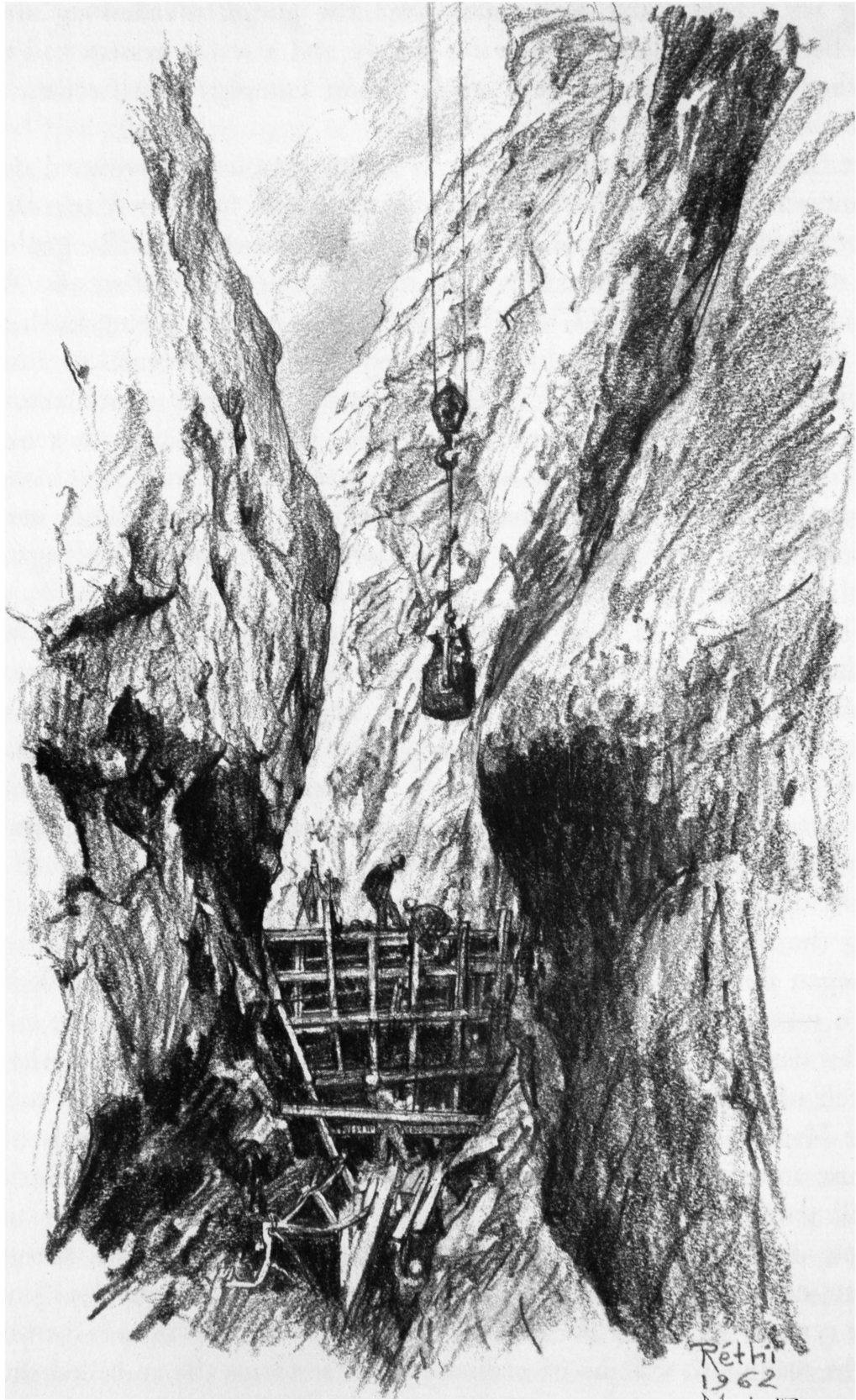
was charged with establishing the initial camp. Although float planes were landing on a lake about four miles from the gorge, a mile-long airstrip had to be built for Manic 5. A water supply and a sewer system had to be established for what would be a small, almost completely self-reliant city.

At the time this advance party was hacking its way northward during the winter of 1959–60, the engineers and designers back in Montreal still had not decided what type of dam would be built at the site. The geologists play a most important role at this stage of such a project. Before the Manic 5 dam could be designed, SNC and Hydro-Quebec geologists had to comb the bush like prospectors searching for gold, because to build a dam with the man-made “rock” called “concrete,” certain natural resources must be found. Most of what the construction prospector seeks is a natural rock product—rock that can be blasted into small pieces for coarse concrete aggregate or rock that nature has already made into gravel; sand, nature’s exceedingly fine gravel; cement, which is also man-made, but, again, is derived from rock; and water.

The availability of these materials is a key factor in determining where and what kind of dam will be built. For example, to build a concrete dam at Manic 5 meant that cement, a manufactured product, would have to be brought in from hundreds of miles away. The transportation of the equivalent of 15 million bags of cement was a staggering logistical consideration. For this reason, among others, Manic 5’s designers automatically considered the possibility of building an embankment of rock and earth instead of a concrete dam.

At the request of Hydro-Quebec, Surveyer, Nenniger & Chênevert in 1959 began an elaborate investigation of the site using diamond-studded core drills to take samples of the rock in the gorge, which would have to support the dam regardless of its type. Teams of geologists roamed the area in search of materials for all types of dams. To build an earth or rock-fill dam at Manic 5 would have required about 40 million cubic yards of fill. And just any dirt or rock would not do for this purpose. Both earth and rock-fill dams must contain a waterproof zone so that the water in the reservoir does not leak through the embankment. Usually this section of the dam, called the core, is built of an impervious soil such as clay. Enough of this type of soil must be within a reasonable distance of the damsite, as must the mammoth volume of ordinary fill that forms the so-called shell of the dam.

Sand and gravel for filter zones must be found for an earth and rock dam. A substitute filter material can be made by blasting solid rock formations and crushing the rock into man-made sand and gravel, but the rock formation must be available. For the shell zones of an embankment, quality of



The very first concrete for Manic 5 is placed in a narrow slot, the absolute bottom of the gorge, which was finally found more than 150 feet below the riverbed.

the fill is not so important as quantity. Probably 90 per cent of the 40 million cubic yards that would have been required at Manic 5 would have been for the shell zones.

If this huge volume of material is too far from the damsite, the cost of transporting it becomes prohibitive. Consider that the average dump truck one sees on the street holds between 5 and 10 cubic yards. Even though today's engineer can use mammoth trucks that haul up to 75 cubic yards, still hundreds of thousands of truckloads would be required to build a 40-million-cubic-yard embankment.

Nevertheless Hydro-Quebec's consulting engineers investigated all the alternative designs of dams that might be used at Manic 5. Based on the preliminary investigations in the field, SNC, working in close collaboration with the famous Paris archdam specialists, André Coyne & Jean Bellier, drew up layouts and estimates for various designs. Eventually, the designers narrowed their choice to either a rock-fill or a multiple-arch concrete dam. More detailed layouts and estimates of these two types finally showed a significant difference in cost favoring the concrete multiple arch.

Again the geologists had to be consulted. A final decision on the multiple-arch design could not be made until the geology of the rock foundations had been studied in more detail. The series of thin concrete arches, like cylinders sliced lengthwise, would lean on giant triangular buttresses. The foundation rock under these buttresses had to be sound enough to support the tremendous forces exerted by the water on the arches, which in turn transmitted them to the buttresses.

The many core samples pulled from the gorge rock told geologists that the site was geologically suitable for a multiple-arch concrete dam. By plotting the make-up of the cores on a topographical section of the gorge, geologists then produced a so-called geologic profile, showing the rock formations below the surface. Joints and fault zones in the rock, which might make a foundation unstable, are located this way.

The bedrock at Manic 5 was moderately jointed, granite-gneiss with a few minor shear zones, mostly on the west bank, but the diamond drills found no major faults that would cause serious design or construction problems. To verify the geologic forecasts of the core samples, the Manic 5 geologists dug trenches down to rock on both banks of the river. An 1100-foot-long inspection tunnel bored into the west bank gave the scientists an opportunity to perform an "internal" on the Manic 5 geology. Tests were run at the site and in the lab on rock samples to determine the rock's coefficient of elasticity.

Although the rock on both banks of the river proved satisfactory, a major problem was discovered in the riverbed itself: the bottom of the gorge, although narrow, lay about 150 feet below the riverbed. Over the centuries

the river's rushing waters had deposited granular material called "alluvium" in the narrow gorge, and now the designers of Manic 5 had to cope with this highly pervious deposit of sand, gravel, and boulders. It would have to be either sealed up or removed, otherwise the water stored behind the dam would seep underneath, eventually washing out the alluvium and allowing the river to flow under the dam.

This deep alluvium deposit in the gorge not only presented problems to the dam designers, but would also complicate construction of the dam, since the river would have to be temporarily blocked off and diverted through tunnels in order to excavate and begin construction of the dam. This diversion structure, called a "cofferdam," would have to be watertight, particularly if the dam builders were going to excavate to bedrock, more than 150 feet below the riverbed.

But the engineers of SNC and Hydro-Quebec did not consider this geological booby trap an insurmountable problem. In the summer of 1960 Hydro-Quebec decided definitely that Manic 5 would be a concrete, multiple-arch dam. Details of how the engineers dealt with the Manicouagan gorge's alluvium—and made engineering history—will follow in a later chapter.

The deep gorge below the river at the Manic 5 site had an interesting effect on the dam's official dimensions. Engineers measure the height of a dam from its crest to its deepest foundation. Usually, the lowest point of its foundation has to be estimated since this point is often under the river. Manic 5 was no exception, and during the very early planning days the dam to be built at the site was generally referred to as a 600-foot-high structure. By 1960, when more was known about the geology, the proposed structure was listed as a 650-foot dam, although its crest level remained the same, at elevation 1200. By the time excavation for the main arch was completed in 1962, the dam's height had increased *downward* another 53 feet, for a record final height of 703 feet.

Design engineers now had the geologists' assurances that the rock foundations would safely support the concrete dam. Next came the search for materials, within a reasonable distance of the site, with which to manufacture the huge volume of concrete required. Manic 5's delicate design, using thin concrete arches, had a direct bearing on the type of sand and aggregate required for the concrete.

A conventional concrete dam, called a "gravity dam," is in simple terms just a huge block of concrete placed in the way of a river. Its weight alone holds back the river water as it piles up behind the dam. The concrete in a gravity dam is under no structural load, except that the concrete at the bottom must support the concrete above it. As long as this mass of concrete is heavy enough to withstand the weight of the water, and adheres tightly enough to the rock to preclude leakage, the structure serves effectively.

Earth and rock-fill dams are also gravity dams. In essence, a concrete gravity dam is merely a densely packed mixture of rock and sand, glued together with a paste made of cement and water. In the concrete gravity dam, the paste has only to be strong enough to hold the rock and sand together. (Actually, a chemical reaction takes place in concrete causing the cement-water paste and the rock and sand to form a rock-like mass.) Well-made concrete becomes so completely integrated that a break will fracture through the larger pieces of crushed stone, rather than separate the components.

But concrete arches, such as those at Manic 5, were not gravity structures. A concrete arch dam is in compression, holding back the water in the same way that a doorway arch supports the wall above it. The doorway arch transmits the load above the doorway to the walls on each side. The arch dam transmits its load to the rock foundations of the river gorge. Concrete is very strong when subjected to compressive forces, although it breaks easily under so-called tensile stress. Because of its compressive strength, it can be used very effectively in an arch structure.



Drill crews, their big crawler drills clinging to the steep slopes, brave Quebec's wintry blasts to carve foundations from the granite gorge.

The most important reason for building an arch dam rather than a gravity dam is to save concrete—a gravity dam at Manic 5 would have used nearly 5 million cubic yards of concrete—but an arch design requires a much better quality of concrete. It will be in compression continuously as long as there is water in the reservoir.

The engineers of Manic 5 had to produce almost 3 million cubic yards of concrete with a compressive strength of 4500 pounds per square inch. In such high-strength concrete, not only must the cement-water paste be stronger, but the sand and aggregate also must meet exacting specifications. So, while the foundation men probed the rock of the gorge, other teams of geologists went into the bush in quest of the 1.7 million tons of sand and 2.5 million tons of rock that would be needed to feed the big concrete mixers.

■ ■ ■ At Baie Comeau, where Hydro-Quebec had decided to establish a headquarters to co-ordinate the entire Manic-Outardes development, an army of construction equipment mustered. To build the 135-mile road, more than fifty bulldozers and a fleet of about one hundred trucks were needed. Resident engineer Fernand Talbot's road-building crews had to clear an 80-foot-wide right-of-way, more or less following the tractor trail through the bush. Talbot's men followed another bunch of bushwackers, the surveyors who established the line and grade of the road with transits and tapes. The surveyors' grade stakes guided the 'dozers and graders that leveled the route, sometimes moving the sides of hills into ravines.

Although plans called for an asphalt-topped road eventually, the initial road was designed as a heavy-duty gravel road, something Canadians are famous for and that many professional drivers prefer to paved roads. (They claim skids are more predictable on gravel than on pavement.) The road's bearing surface would be 30 feet wide normally, but would widen to 36 feet at sharp curves and steep grades. In order to avoid too many curves and steep grades, Talbot's men were to blast more than 750,000 cubic yards of rock and use it for fill in marshy sections before the road to Manic 5 was complete. Screening plants set up at the few gravel pits found along the route would process 2 million cubic yards of gravel for the road's bearing surface.

Although seemingly of comparatively minor importance, construction of a top-notch road was essential. Besides the 700,000 tons of cement to be trucked to Manic 5, there would be steel for the many tunnels to be drilled, monstrous steel tubes for lining the powerhouse penstocks, hundreds of buildings, huge cranes, and three auxiliary diesel-electric generators the size of railroad locomotives to power the camp until linemen could string a 115,000-volt transmission line northward from Baie Comeau. The road to Manic 5 would undergo more wear and tear in ten years than most roads get in fifty years.

Long before the permanent road reached the site, the camp began taking shape. Loggers had cleared much of the area, setting up a small sawmill and turning the so-called slash into lumber for the camp construction. It was September of 1960 when Talbot proudly drove Oscar Cantin 90 miles north on his new road. But from Mile 90 on, Cantin had to take to the air. His air taxi, a Beaver float plane, touched down 4 miles west of the damsite on Lac Louise to find the advance party well established. Bulldozers were already at work on an airstrip near the lake. The 5500-foot-long gravel runway would make the in-bound trip considerably easier, at least for people and some types of freight.

The men who had come in over the tractor trail lived in a camp comprised of about twenty tents, one a kitchen. At this point, the amenities of home were hard to find at Manic 5. Cantin's assignment was to supervise erection of the permanent camp buildings, which were to be hauled in on sleds by the crawler tractors. He and his bushlogging crew also had to build a temporary Bailey bridge over the river below the damsite, as the rushing torrent made access to the east bank impossible for heavy equipment.

Since the bridge needed concrete abutments on both sides, obviously Cantin's men had to get some equipment across the river. The mode of transport was simple. A barge-ferry was put in operation upstream of the waterfalls, just above the damsite. This done, crews completed the big steel-truss Bailey bridge, which was to serve for eight years. This was built about 2000 feet downstream of the dam axis and was designed to handle the heaviest equipment that might ever be used on the project.

During the winter of 1959-60 the big tractors dragged in components for eleven buildings. The standard camp structure was a steel-framed, gable-roofed building sheathed in galvanized sheet steel. The 32×164-foot buildings, referred to individually as "camps," slept up to sixty-three men.

"By the fifteenth of December we had nine camps up," Cantin remembers. "But the first three were the most important after living in those tents. After we got our first bunkhouse up and we could put in a shower bath, then it was pretty good. We moved the kitchen into one of them, and of course once we got a few camps up, we could bring in more men."

During that winter, each extra man was important. "One of the bad things was our heating system that winter," Cantin recalls. "With no road, the oil that was sledged in was needed for fuel for the machinery. We didn't have heating oil, so we made stoves of 45-gallon drums and burned wood. We kept twelve or fifteen men cutting firewood all the time."

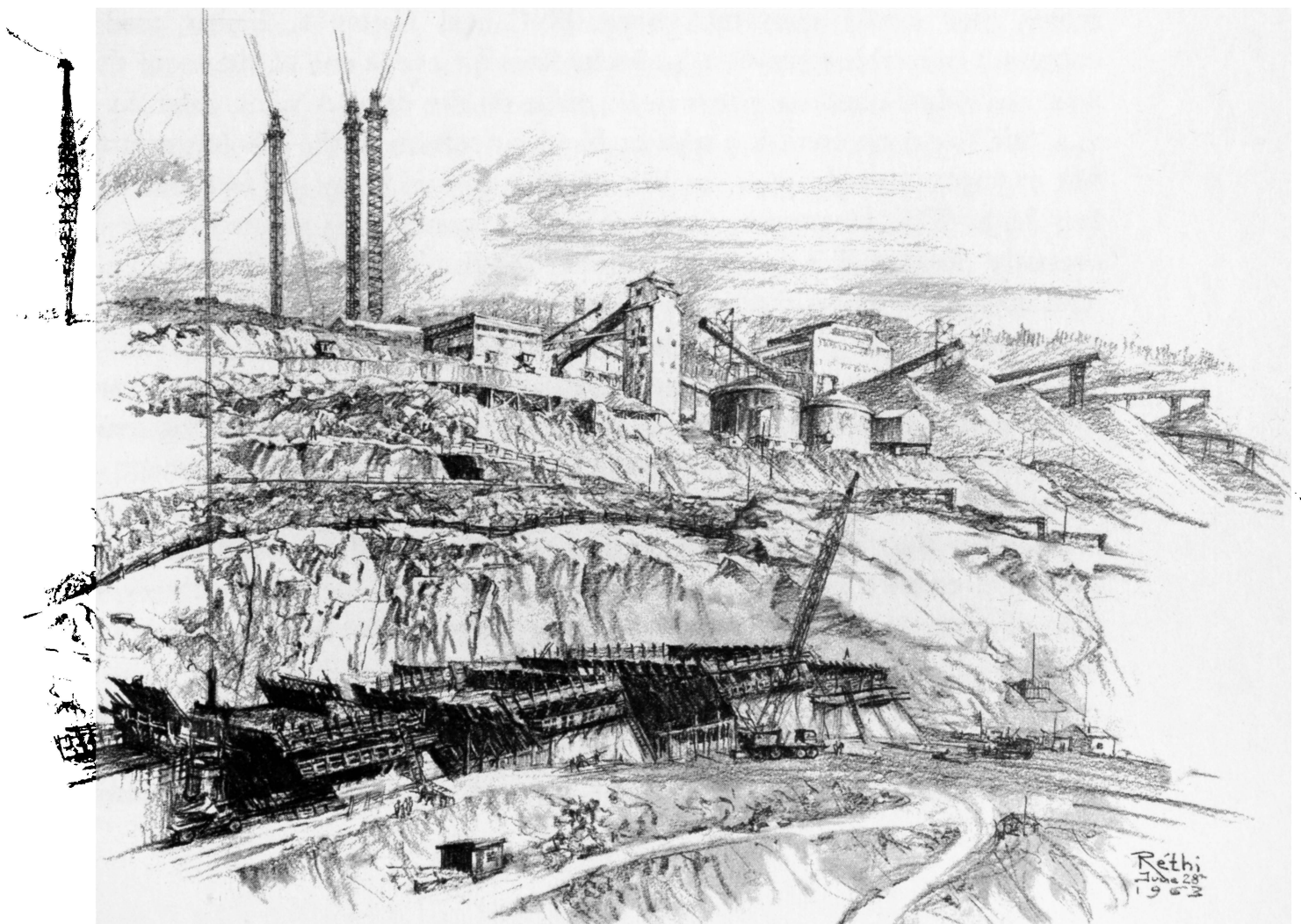
As is typical in the mountainous country where dams usually are built, there was no level area on which Oscar Cantin could build his camp: "We 'dozed the mountainside down to form the camp site." The big mess-hall

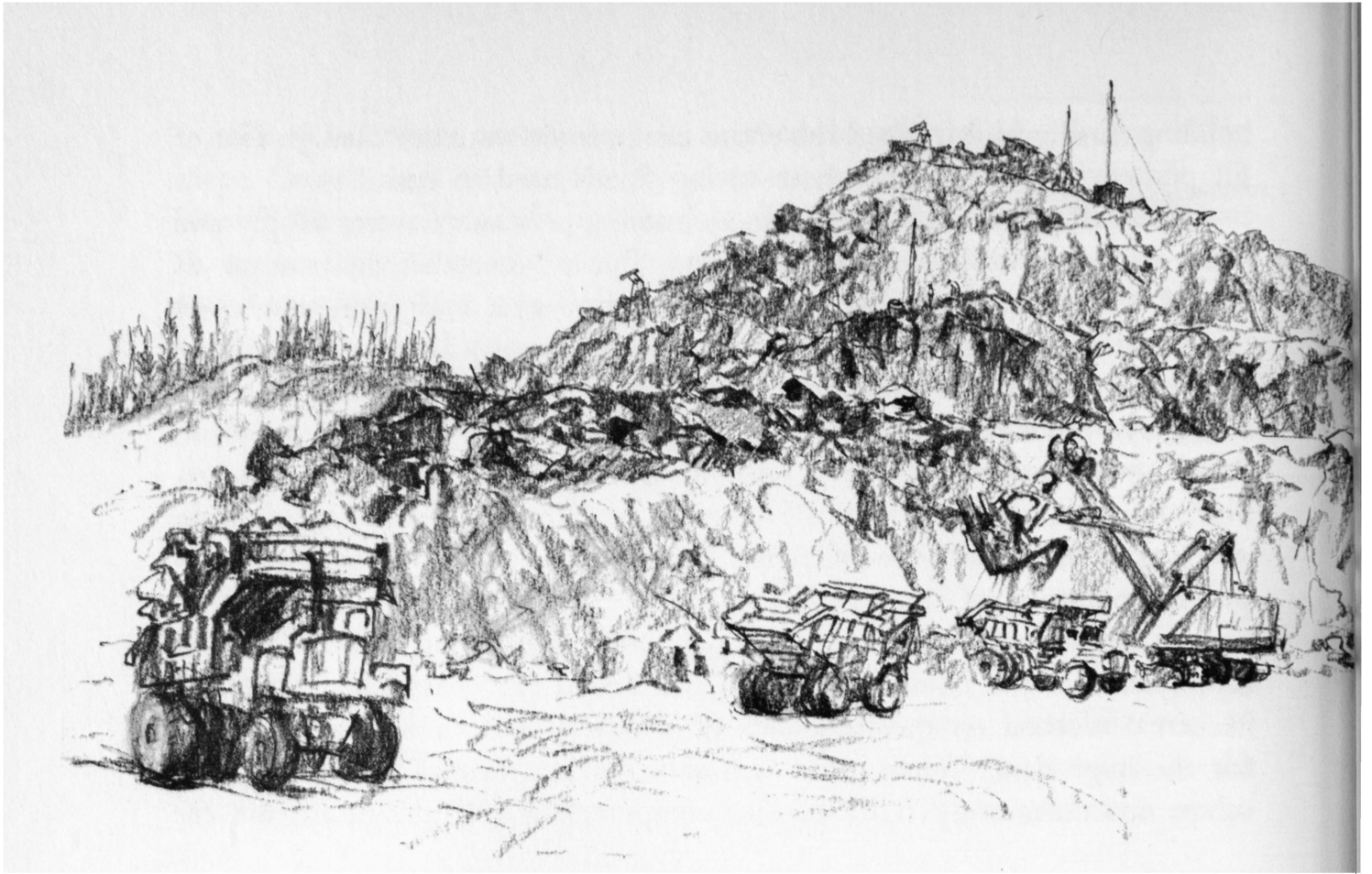
building, finally built to feed the entire camp, stood on more than 30 feet of fill pushed into the gorge where spring floods used to run.

Original plans called for Cantin to install a permanent water supply and sewer system to serve the full-scale camp, "But in November the frost got us so bad we had to run in a temporary line and cover it with insulation," said Cantin. It was not until the spring of 1960 that crews were able to install permanent utilities. A small lake located up on the west bank about 125 feet above the elevation of the camp was a natural for the water reservoir. Pumping was unnecessary as gravity would supply water at high pressure. Since the Manic 5 camp would eventually develop into a small city, Cantin also had to build a sewage-collection system and a small treatment plant to prevent pollution of the river.

As engineers, geologists, lumbermen, and construction workers labored side-by-side in the inhospitable bush, the design engineers and planners in Montreal worked on the thousands of drawings and calculations required for the huge dam. While some men shivered in front of oil-drum stoves, others 600 miles away fed data into computers, which ultimately told the

Concrete producing complex on east-bank slope dominates the project as base of main buttress begins to rise from its rock foundation.

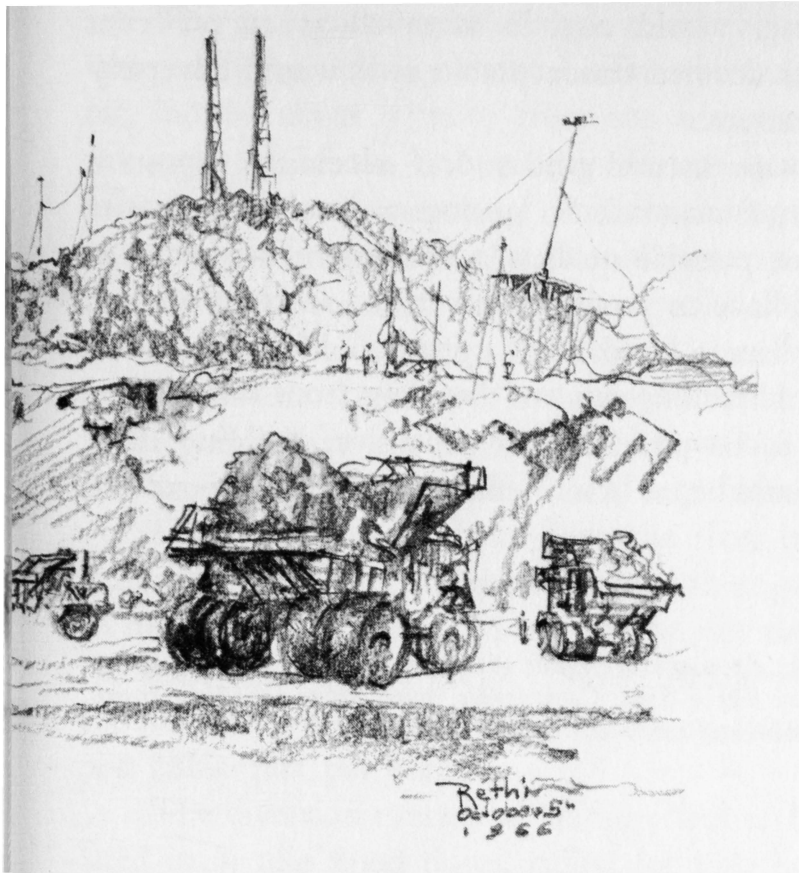




design men exactly how and where to place the string of graceful concrete arches that would span the gorge. SNC and Coyne & Bellier used a computer to establish surveyor's checkpoints for every one of the more than 8000 individual concrete pours to be made on the dam. A pour, referred to as a "lift" by concreters, is a specific block or section of the whole structure. For example, a single pour, or lift, might measure 30 by 50 feet and be 5 feet high. The formwork, into which the concrete is poured, must be precisely positioned in order to maintain the dam's designed configurations. The computers saved thousands of man-hours, establishing in advance the exact elevation and horizontal location of every block.

While the dam took shape on paper, a hardy group of geologists pressed their search out in the bush for the materials with which to create the structure's concrete. Each cubic yard would require 394 pounds of cement, to be trucked in to the site. But this cement, mixed with 190 pounds of water, forms only the paste that glues together 1225 pounds of sand and 2290 pounds of crushed rock. This 2-ton recipe results in a block of concrete only three feet square and three feet high. The geologists were looking for enough sand and rock to make 3 *million* such blocks.

Obviously, the Manicouagan River could easily provide the approximately 72 million gallons of water that would go into the concrete. (Sometimes, however, ordinary river water contains the wrong minerals and is



Drillers and powdermen blast away a mountaintop, creating a quarry that provides as much as 10,000 tons of rock each day. Giant trucks haul shot rock to crushers that make it into concrete aggregate.

unsuitable for concrete mix water.) Good, solid, granite-gneiss rock was close at hand and a quarry could be located near the damsite to feed blasted rock into a giant crushing and screening plant. This quarry would have to supply millions of tons of rock from the mountainside. To keep up with the big concrete mixers it would have to provide nearly 10,000 tons of rock each day. But this could be done; not easily, but the rock was there in a big outcropping on the east bank reasonably close to the site. The coarse aggregate was plentiful.

The geologists had to find one last important ingredient for the concrete—sand. As the glaciers receded, their melting ice formed raging streams that left many deposits of sand in the region. But Manic 5's builders needed 1.7 million tons of sand and it had to be of the proper quality for concrete with a compressive strength of 4500 pounds per square inch. Both the shape and the distribution of the grain sizes had to be correct. A dozen sand deposits turned up within a 5-mile radius of the site, but the quality was not always acceptable.

Since the plant that would crush and screen the coarse aggregate had been designed so it could manufacture sand if necessary, engineers considered the possibility of making their own sand from the native rock. Unfortunately, investigations of all the possible economical quarry sites showed too much biotite, a form of mica. Tests showed that the granite-

gneiss, when crushed into sand, would contain as much as 10 per cent biotite, which concrete experts deemed unacceptable as it would adversely affect the strength of the concrete.

This left no choice but to use natural sand and, if necessary, process it to provide the proper quality of material. So geologists headed back into the woods looking for the most passable quality in the largest deposit. The sand-classification plant would have to process more than 4000 tons of sand daily and cost over a million dollars to build. Such a plant could not be moved from one deposit to another, and hauling sand to the plant from four or five different deposits was bound to be prohibitively expensive. Building more than one classification plant would be, at best, inefficient. A large deposit had to be found.

By July of 1963 Manic 5's main arch has risen out of the narrow gorge and begins to look more like a dam. Concreters, with more working room, now can speed up placement with the aerial cableways.



The geologists extended their search beyond the 5-mile limit and were lucky with an unlucky number. The thirteenth sand deposit discovered so far, located about 7 miles from the site, turned out to be large enough, although not of the best quality. It was heterogeneously mixed and contained 30 to 40 per cent of unacceptable gravel. There was also a high percentage of fine sand that would have to be discarded. But even with the waste, G-13, as the sand pit was labeled, could supply the final ingredient for the Manic 5 concrete.

So the concrete could be manufactured; all the ingredients had been found except for the cement, which would be brought in. But the first bucket of concrete was still a long way from being placed in Manicouagan gorge. In order to build the dam, the river had to be diverted around the damsite. Considering the steep narrow river gorge, there was only one way to do this—the river would have to be put through tunnels driven through the rock walls of the gorge. These tunnels would have to handle not only the normal flow of the river, but also the heavy spring flood of about 100,000 cubic feet per second.

The diversion tunnels at Manic 5 had to be big—the final design, calculated to handle flood flows, called for two horseshoe-shaped bores 47 feet high (each larger than a two-lane highway tunnel). Obviously, the longer the tunnels, the more they would cost and the more time it would take to drive them. Engineers, again consulting with geologists, decided to build twin 2200-foot tunnels in the west abutment, although this meant that the intake portals would be less than 1000 feet upstream from the dam's axis.

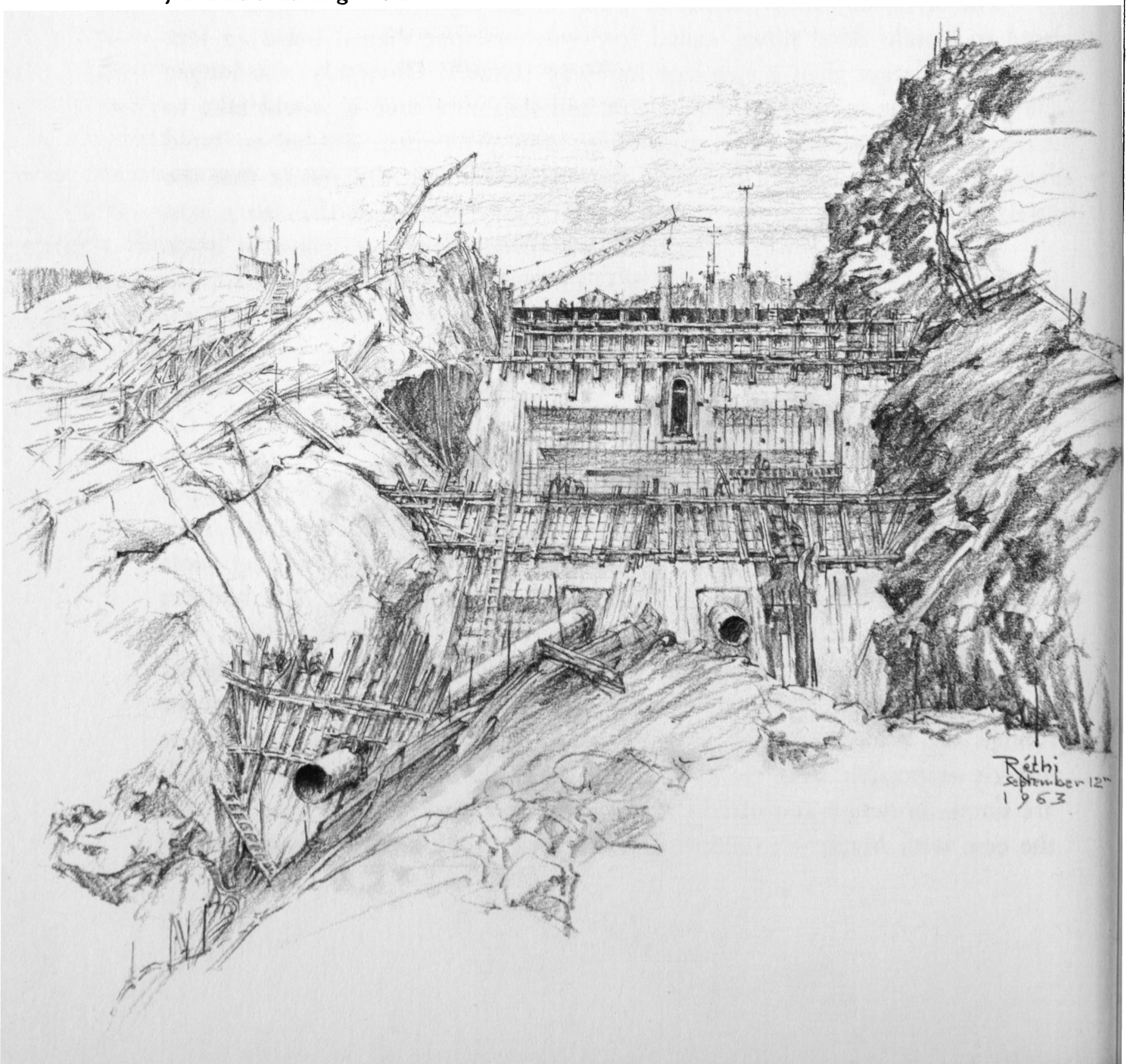
This first-stage construction on a dam project, although taken in stride by dam builders, would alone qualify as a major construction project in most other engineering circles. The basic concept of diverting a river this way is a sticky business at best. Diversion tunnels generally are built at an elevation equal to or below that of the river in order to divert the flow without having to raise the river's level. Driving most of the tunnel from the downstream end and protecting the portal with a dike can be done with relative ease. But eventually the upstream end of the bore must be opened. To keep the river from entering the incompleated tunnel an even more elaborate dike must protect the upstream portal. To avoid building these extensive protective works around the portals of such tunnels, dam builders try to complete diversion tunnels quickly between the flood seasons.

Although the river cannot be blocked off entirely until the tunnels are finished and ready to handle flows, designers usually begin this work as the tunnels are being built, the ultimate goal being to plug off the stream as quickly as possible once the tunnels are ready. In a sense, diversion tunnels are simple in design and often they need not be lined with concrete, as was the case with Manic 5's tunnels. But one aspect of diversion tunnels is not

common to all tunnels: ultimately they must be plugged to impound the water in the reservoir. At Manic 5 huge steel gates were built at the upstream end of the diversion tunnels. Like the tunnels themselves, these gates would be used only once. The tunnels would serve continuously for a matter of years, of course; but the gates would be closed once and never opened again. Once the gates were closed, concrete would plug the tunnels and they also would have outlived their usefulness.

In early 1961 Hydro-Quebec awarded a contract for \$2.7 million to Janin Construction Company, of Montreal, for construction of the diversion tunnels. Oscar Cantin's men had, by this time, established an impressive construction camp. Hydro-Quebec crews had blasted and excavated the mountainside down to the tunnel face where Janin would begin tunneling. A dike was built to protect the tunnelers, and in May of 1961 Janin's hard-rock specialists moved onto the project.

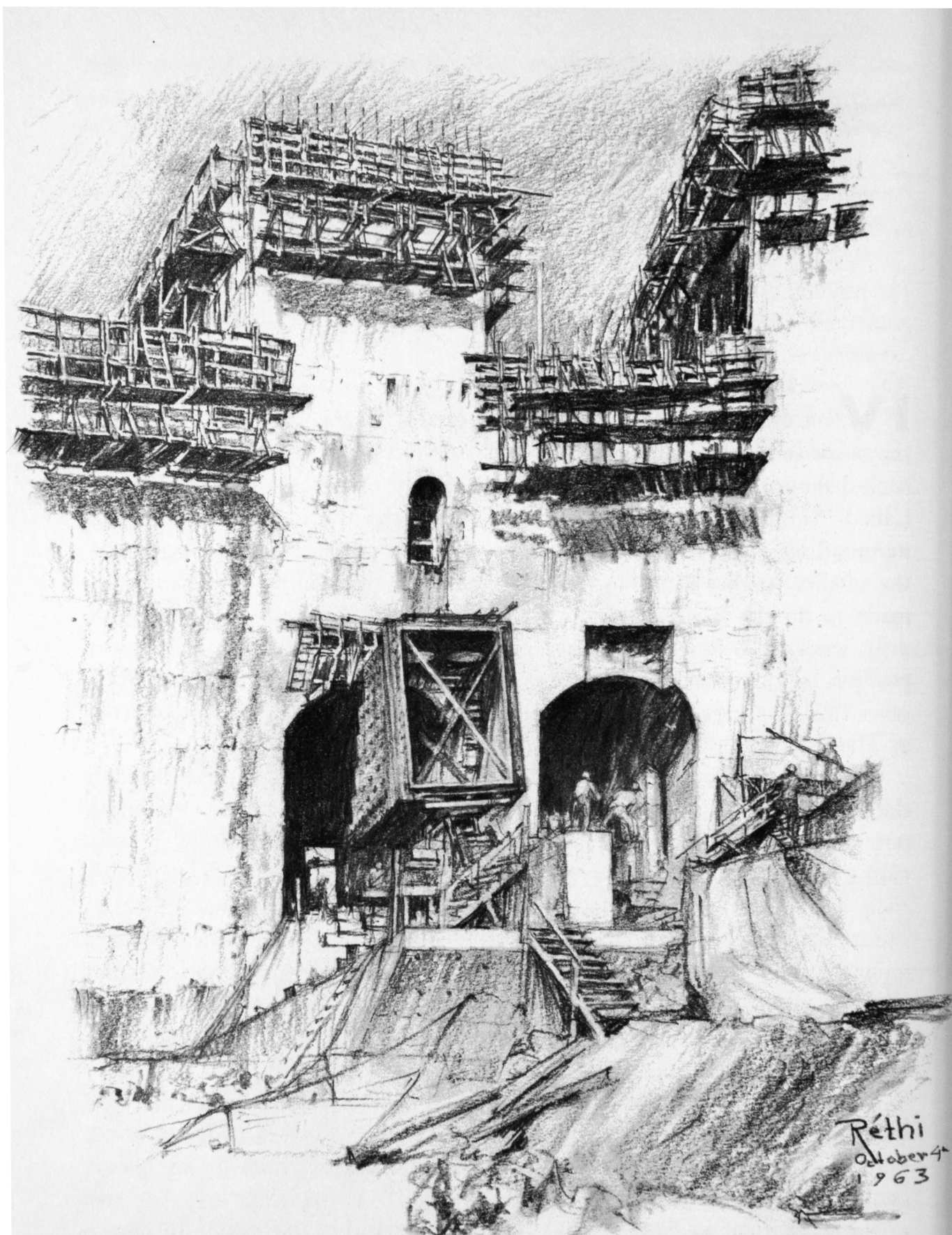
View from upstream clearly shows juncture where two arches converge to share common support of single buttress. Concreting has barely emerged from surrounding rock.



IV Construction of the diversion tunnels, like nearly every phase of the work at Manic 5, was anything but routine. Janin decided to try a new rock-drilling technique developed in Sweden by the Atlas Copco Company. Called "ladder drilling," the method involves the use of lightweight drills mounted on a ladder-like steel carriage. Because of the ladder arrangement, the smaller jackleg drills, normally operated by one man as a hand tool, are made to do the work of much heavier machines. Not only are the small drills less costly, but they are also more efficient as the technique makes it possible for one man to operate two drills at the same time. So the method saves time and cuts both capital and labor costs. Janin's use of ladder drills at Manic 5 was the first such operation in North America.

Janin's tunnelers otherwise used conventional methods to drive through the hard gneiss rock of the west bank. The basic method involved drilling a series of holes in the rock face, charging the holes with explosives, detonating the charge, and, finally, excavating the blasted rock fragments. Janin's rock drillers worked on a large multideck mobile platform that tunnelers call a "drill jumbo." A jumbo has four steel decks on which the drills are mounted and their operators stand. The ladders that carry the drills are movable, mounted on hydraulically operated booms, sometimes called "jibs." The driller positions the drill by maneuvering the jib and ladder with hydraulic valves.

The actual drilling for a tunnel is complicated. Depending on the type and condition of the rock, holes must be precisely placed in order to break out the desired amount of rock and, at the same time, blast it into pieces small enough to be excavated, or "mucked out," as tunnelers say. The size of the holes, their spacing, and the depth to which they are drilled all have a bearing on the success of each shot. The type and amount of explosive used is another key consideration. But even more important is the timing of the explosions in the various holes. Unlike a blast on the surface, the tunnel blast must not only be engineered so the rock shatters, but it must also throw the shattered rock into the tunnel. In other words, the tunneler is attempting



Réthi
October 4
1963

Steel liner goes in place for outlet control works, two big low-level sluices near bottom of main arch. These are needed to maintain flows downstream after diversion tunnels are plugged.

to create a particular size bore through the rock, while doing as little damage as possible to the surrounding rock. The blasting in a tunnel, therefore, is highly controlled.

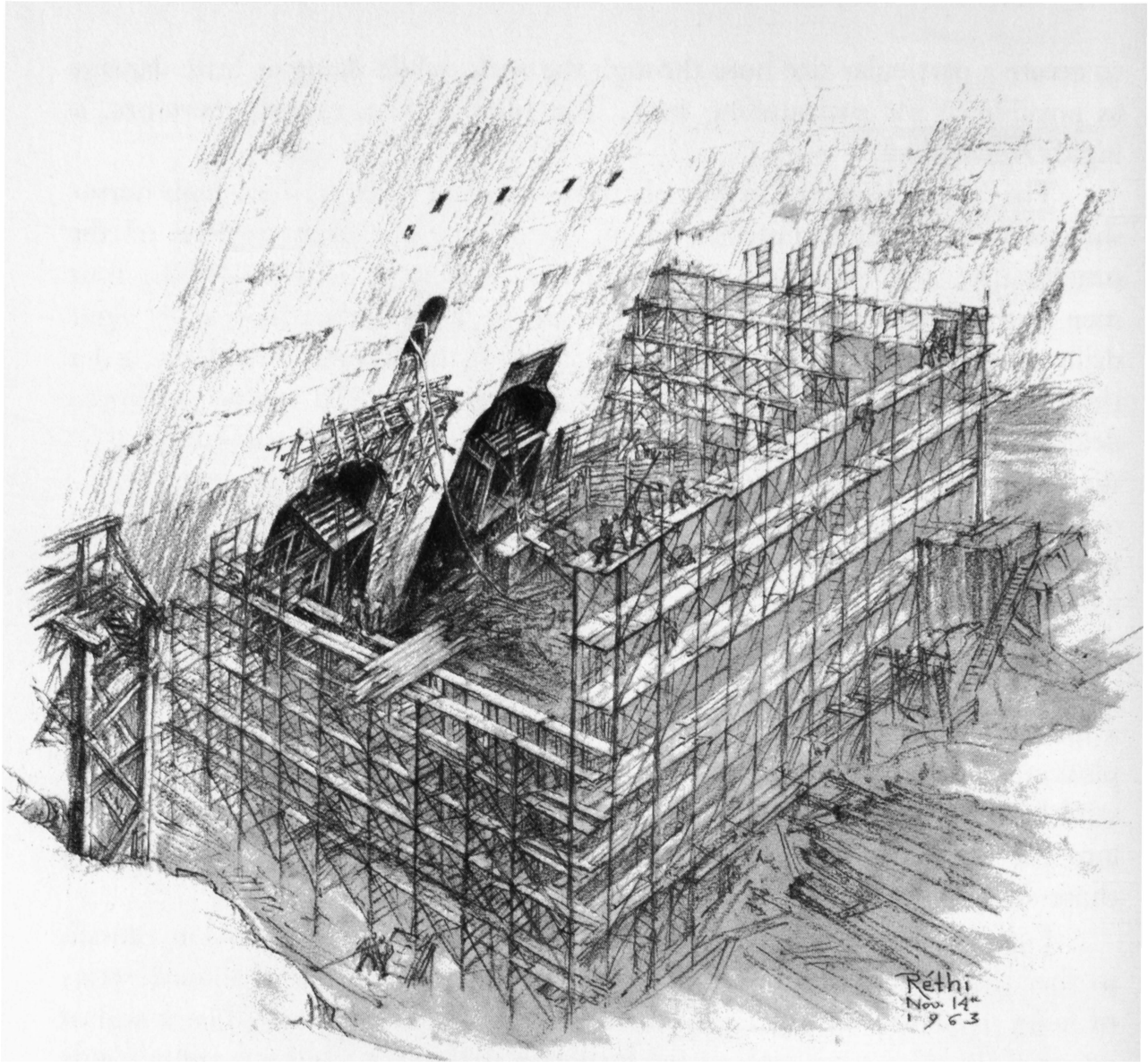
The Manic 5 diversion tunnels were designed to be 47-foot-high horse-shoe sections; Janin's tunnelers began by driving the arch sections of the tunnels first. Drillers, three on the jumbo's top deck with six drills, four men with eight drills on two intermediate decks, and five men with eight drills on the lower deck, drilled a total of 158 holes each round. In order thoroughly to break the rock while not making the tunnel too large, Janin's drillers used what is known as a "V-cut"—three rows of holes, roughly in the center of the face and parallel to the floor of the tunnel, drilled obliquely. The holes nearest the center were angled toward the tunnel's centerline quite sharply, with this angle reducing with each successive hole until the outermost holes were straight on, along the wall of the bore. All the remaining holes were drilled parallel to the line of the tunnel.

Here is where the timing of the detonations plays its role. Although a blast, called a "shot" by tunnelers, appears and sounds like a single explosion generally—there is in fact a series of explosions, detonated thousandths of a second apart. Tiny devices called "blasting delays" are wired into the circuit so that the explosives in some holes detonate sooner than those in other holes.

For example, Janin rigged the delays in the Manic 5 diversion tunnels so that the explosives nearest the center of the face in the V-shaped series of holes fired first. Charges in the next holes fired one millisecond later and so on, until the outermost holes of the wedge of rock fired a full ten milliseconds after the center holes. Although all this takes place in a matter of one hundredth of a second, followed by the main blast in all the other holes, it nevertheless causes the wedge-shaped section of rock to move away from the face first, thus creating some place for the other rock to go when it shatters. The last charges to fire are in the row of holes that outline the perimeter of the tunnel.

On the advice of blasting experts from Canadian Industries Limited, which was supplying the explosives, Janin used a special controlled blasting agent in these perimeter holes. The idea was to cause the rock to crack between each perimeter hole without shattering beyond the perimeter. If this is not done, the shot causes overbreak and cracked rock beyond the tunnel's perimeter that must be scaled off with crowbars, if only for safety's sake.

Using this method, Janin's tunnelers advanced an average of 14 feet per round, a round being one complete cycle of drilling, shooting, and mucking. The cycle works like this: the jumbo is rolled into place; the air-powered rock drills sink all the necessary holes; the explosives men charge the holes,



Elaborate steel pipe scaffolding, being erected for construction of the outlet control works at the base of the main arch, brings to mind the spindly bamboo scaffolds used on construction jobs in the Orient.

shoving individual sticks of dynamite into the holes with wooden poles; electric blasting caps and delays are wired up and the shot is ready.

The jumbo must then be moved back from the heading. The jumbo is built in the shape of an arch so that its inner platforms fold down out of the way. It is built this way so that mucking equipment can drive through it. In other words, the jumbo need not be removed from the tunnel; it is merely moved back from the face far enough to protect it from the explosion. The trucks, or small railroad trains sometimes used in tunnels, are able to pass through the jumbo as they remove the shot rock.

Once men and equipment are moved back from the face a safe distance (in a short tunnel or the early stages of any tunnel, the jumbo and other equipment are taken out of the tunnel for a blast), the explosives are set off. After the shot, the tunnel's ventilation system, usually a large steel pipeline

suspended from the tunnel roof to supply fresh air, is run in reverse to exhaust dust, smoke, and fumes caused by the explosion. At Manic 5, Janin's big fans usually exhausted for about twenty minutes to clear the air for the mucking operations. Thus when the fans began pumping fresh air into the face, mucking crews moved to the heading.

Janin loaded out the shot rock at Manic 5 with big crawler tractors, mounted with front-end loaders and side-dump buckets. The side-dump buckets allowed the tractors to load trucks without having to pivot sideways. The trucks backed in alongside the loaders, and when the loader had scooped up a bucket of shot rock, it merely backed up and dumped into the truck's body. Janin's mucking crews took out an average of 500 cubic yards of broken rock per round, averaging around four and a half hours for that part of the cycle.

Janin started the tunnels in the spring of 1961 with a tough deadline to meet. The big bores had to be finished and ready to handle the mighty Manicouagan's flood flows when the spring thaw came in 1962. But the combination of good sound rock and the contractors' pioneering methods resulted in a finish ahead of schedule. Janin holed through the twin tunnels' arch sections and then the tunnel crews returned to blast out the bench sections, the lower portions of the horseshoe cross section.

The quality of the rock encountered in tunneling is important for two reasons. If the rock is good, there will be less overbreak, which means less muck must be excavated. And a tunnel through sound rock will be self-supporting, i.e., the tunnelers will not have to install steel supports or rock bolts. Steel supports are usually heavy steel ribs placed fairly close together to keep the tunnel from caving in. Rock bolts can sometimes be used for the same purpose; these are just what their name implies—long steel anchor bolts installed in holes drilled into the roof and walls of a tunnel. These bolts effectively pin the rock around the tunnel's perimeter to undisturbed rock farther away.

The rock Janin drove through in the Manicouagan's west bank was of such good quality that no steel supports and only a few rock bolts were required. And Janin finished the two big tunnels in only six months. By November of 1961 the tunnelers had succeeded in providing a new route for the Manicouagan River.

But driving the two big hard-rock tunnels was only half the task of diverting the unruly river—the easy half, at that. At some damsites, a river can be diverted into tunnels or a diversion channel by building a relatively simple dike across the river just downstream from the entrance of the tunnels or channel. The dam is then built behind the dike.

Manic 5's engineers were faced with a far more complex problem—the alluvium-filled, 150-foot-deep rock gorge, below the riverbed. Although

the geology of the surrounding mountainsides was sound (examinations of the rock in the diversion tunnels had borne out the geologists' predictions), this deposit would serve perfectly as the course for an underground river that would most effectively drain Manic 5's reservoir. In fact, if it were not sealed, it was doubtful that the huge impoundment would ever fill in the first place. Most alarming of all, if water were to seep through the alluvium under the dam, it would eventually wash out the deposit and threaten the foundation of the dam.

Further complicating the situation, test borings showed that the gorge extended even deeper at the point where the upstream cofferdam had to be built. In this reach of the river, a bare 600 feet upstream from the axis of the dam, the alluvium deposits went down at least 200 feet. The dam designers had decided that the foundations for the concrete arches must be in sound rock. This obviously included the central arch that straddled the deep river gorge. So the alluvium would have to be excavated completely from the gorge and replaced with concrete, a challenging job in its own right. But more vexing was the problem of keeping this narrow but deep excavation dry. The cofferdam dike would divert the main flow of the river into the tunnels, but in order to excavate nearly 200 feet below the level of the river downstream from the cofferdam, engineers had to make the cofferdam as close to 100 per cent watertight as possible. The delicate job of cleaning out the narrow cavity and filling it with concrete, often called "dental work" by construction men, could not be done in soggy conditions. For one thing, geologists and engineers wanted to examine the deep-seated rock. The upstream cofferdam had to be tight, yet the alluvial deposits in the gorge ran even deeper at the axis of the cofferdam than at the dam's axis.

Not only was the gorge deeper where the cofferdam had to go, but it also was wider. This meant a greater cross-sectional area had to be sealed against seepage. And there was always the nagging deadline: the entire diversion scheme had to be accomplished in one construction season. The cofferdams (a second one had to be built downstream to keep the discharge of the tunnels from draining into the excavation) had to be built and sealed within seven to eight months. So time was a major consideration. Naturally the cost of the cofferdam seal had a bearing on the over-all problem, in that the structure was only temporary and was to serve only long enough for the workers to excavate the gorge, plug it with concrete, and raise the main arch to a level slightly above the tunnel portals.

In choosing a method to guarantee the watertightness of the cofferdams (particularly the upstream one), Hydro-Quebec and its consultants called in a special board of experts, a panel of engineers with experience in dam-building around the world. The board, comprised of J. E. Hurtubise, Dr. Arthur Casagrande, and H. E. Barnett, considered various alternatives. It

was generally accepted that the upstream cofferdam had to have a so-called impervious cutoff that extended through the alluvium to rock. The downstream cofferdam would have to be similarly sealed, but the gorge was only 80 feet deep at that point, a relatively minor problem compared to that requiring the 200-foot-plus cutoff upstream.

The upstream cofferdam had to be tight for one other reason. Like the main concrete dam, the cofferdam also could be endangered by seepage underneath it. In fact, seepage under an earth or rock embankment will trigger sliding and collapse even more quickly than in the case of a concrete structure. The experts even went so far as to consider not building an earth and rock dike at all. A thin concrete arch built on concrete gravity base sections was considered but ruled out mainly because it would probably have taken too long to build. Also, the riverbed would have had to be dredged to make way for the concrete, an aspect of the work that could have proved very difficult in winter.

Another device for creating an impervious cutoff for a temporary structure such as the Manic 5 cofferdam is an ice diaphragm. This is made by sinking pipes down through the earth dike and into the alluvium. Refrigerant, circulated through this row of pipes, freezes the soil near them and creates an impervious wall of frozen material. But the consensus was against this method at Manic 5 because the alluvium was so pervious; it might have been very difficult, if not impossible, to freeze. To be frozen, water moving through the soil must be stopped long enough to freeze it initially.

The experts also considered building a dike with an impervious core comprised of glacial till, which was readily available. This involved digging a trench along the axis of the embankment and backfilling the trench with impervious material. Several factors ruled this out: the intakes to the diversion tunnels were so close that working space available for such an approach was too limited. Also, handling the mucky glacial till in winter weather is very difficult, sometimes impossible.

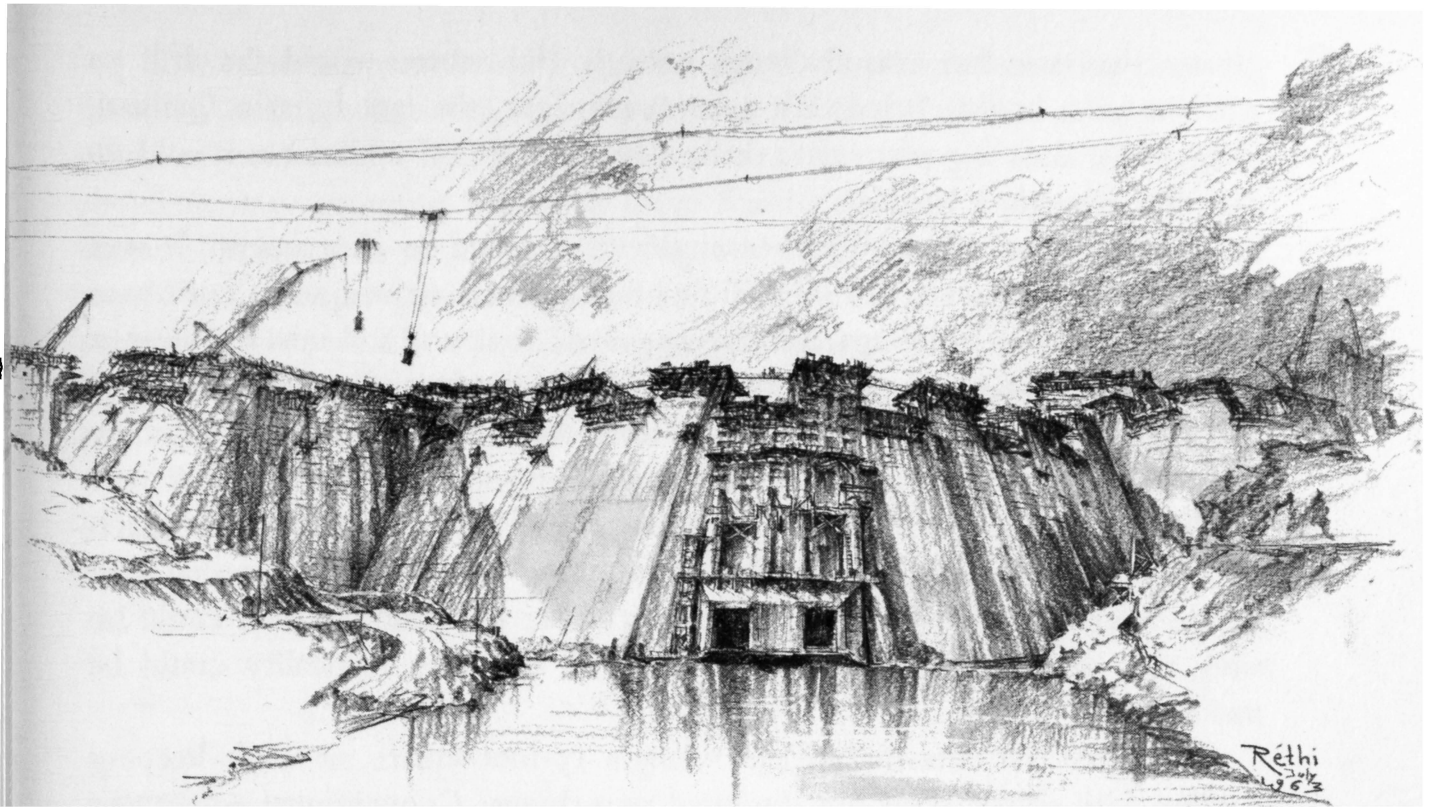
A fourth alternative, which at first seems the most logical, was pressure grouting. This involves drilling holes in the soil, fill, or rock (whatever is to be grouted) and pumping a mixture of cement and water (grout) down the holes. The idea here is that the grout finds its way into the soil surrounding the drilled hole and sets, thus rendering the soil impervious. Although there are many types of grout, even some chemical mixtures that gel almost immediately, grouting to create a so-called grout curtain can be very difficult in highly pervious formations. The water moving through the soil is again the culprit. It washes away the grout before the latter has time to set. Nevertheless, the experts advising at Manic 5 did feel that a grout curtain could be built for the upstream cofferdam. But its reliability would have to be assured by multiple rows of grout holes. Because of the high

water pressures the curtain would be subjected to when the dam foundations were excavated, the panel recommended five rows of grout holes. Although grout curtains are commonly used to guarantee the foundations of permanent dams, the situation at Manic 5 would be considerably different. Assuming the cofferdam to be a permanent structure, the grout curtain would no doubt have served effectively. But at Manic 5 they were going to dig a hole directly behind the structure 150 feet deep. The grout curtain would thus have to sustain pressures equivalent to more than a 200-foot hydrostatic head of water (the pressure developed at the bottom of a 1-foot-diameter column of water 200 feet high).

The board of experts did not rule out a grout curtain for the upstream cofferdam. In fact, it was agreed that a special method of grouting, developed by the Soletanche-Rodio Company, of Paris, and proven at several deep-curtain applications on dams in both Europe and North America, would be used for the downstream cofferdam. A grout curtain was held in abeyance for the upstream project, while a fifth approach was explored.

Several companies around the world had, at the time, developed methods for building concrete diaphragms in soil without excavating a large trench. Called "cast-in-place concrete pile diaphragms," or "membranes," these were generally built in one of two ways. Probably the first method developed was to drive heavy steel casings (pipes) into the ground. Once each such hollow tube is in place, usually in contact with rock, the soil inside is removed and the space filled with concrete. Placing a series of these in a row, if done with great precision, creates a kind of concrete wall in the soil. The other method, relatively new in the early 1960s when Manic 5 was started, is similar in concept except that the steel casing is not used. Circular holes are drilled, but instead of the steel holding the soil in place, a slurry made of bentonite clay and water is kept in the hole as it is drilled. The slurry has a specific gravity slightly higher than that of water and as a result keeps the walls of the hole from caving in. Amazingly enough, this works even in sandy soil and, indeed, the bentonite slurry works its way out into the surrounding soil and creates a kind of secondary seal after the wall is finished.

The concrete is placed in this slurry-filled hole by pouring it by what is called the "tremie method." A long pipe is placed down the hole and concrete flows to the bottom where it displaces the slurry. The open end of the tube is kept in the concrete, but is slowly withdrawn from the hole as the column of concrete grows. The next hole is drilled not immediately adjacent, but one hole diameter away. Once the two concrete columns (piles) have hardened, a special-shaped drill sinks a hole between them. This drill bit has a cross section that is roughly flat on two sides (those parallel to the line of the wall). Its other two sides are concave and expansible



Manic 5 impounds its first water, a small quantity admitted to the area between the dam and the upstream cofferdam. At this time the river is still being shunted through the diversion tunnels (out of sight in this view).

so they fit against the two columns already cast. Using the same bentonite slurry, this bastard-shaped hole is dug between the two standard piles and tremie-concreted. In this leapfrog fashion a very reliable wall is cast, only about 2 feet thick, but watertight.

Since the alluvium in the Manicouagan gorge contained boulders up to 4 and 5 feet in diameter, driving the steel casings was ruled out. But previous experience by an Italian company that had developed the cutoff method had proved that the drilled-in piles could be installed despite large boulders. Whether they could be sunk to such great depths, however, was still a question. The Italians—the parent firm was Impresa Costruzioni Opere Specializzate (ICOS)—had built concrete membrane cutoffs as deep as 170 feet, using their patented ICOS-Veder method. Representatives of the Milan company's North American branch, Icanda Limited, of Montreal, huddled with Hydro-Quebec personnel, the panel of experts, and SNC engineers.

Aside from the basic problem—making a cutoff this deep had never been done before—there were the more precise engineering worries. Could the slender holes be drilled and kept well enough aligned to create a positive seal? Drilling an uncased hole through unconsolidated material to depths

greater than 200 feet was challenge enough. But where would the drill go when it hit a boulder? Icanda's general manager, the late Ignazio Galbiati, insisted that their big percussion drills would not go off course but would go directly through a boulder.

To find out, Hydro-Quebec engineers decided to experiment. It was February of 1961, even before Janin's tunnelers had arrived and Cantin was still erecting camp buildings. Bulldozers shoved rock and soil into the river at the general location of the future upstream cofferdam, forming a kind of jetty on which to perform the various tests. All concerned wanted to know what kind of progress could be made excavating in the alluvium; how well the bentonite slurry would stabilize the walls of an excavation; how much bentonite would disappear into the surrounding soil (since the special clay would have to be imported to the site); whether the concrete piles could be sunk that deep; and, most crucial, how well the piles verticality could be maintained.

The first test consisted of excavating a 15-foot-square pit while keeping it filled with slurry. This test disclosed two things: Conventional equipment such as clamshell and orange-peel buckets would not handle the alluvium in the slurry medium, but, happily, the bentonite slurry did not dissipate too rapidly. It could be controlled in the very pervious alluvium. Convinced of these facts, Hydro-Quebec invited Icanda to its frigid experiment grounds. (Some of Icanda's technicians, fresh from projects in balmy Africa and Latin America, must have despaired at the prospects of even experimenting at Manicouagan, let alone installing an entire cutoff wall.)

But an Icanda crew came to the north country and showed their stuff. Using makeshift drilling equipment, since time precluded bringing in one of their special rigs, Galbiati's men sank a 100-foot-deep pile into the alluvium from the jetty. In the small, 2-foot-diameter hole the bentonite slurry held the walls of the hole. Only a moderate amount of the continuously circulated slurry impregnated the alluvium and, best of all, Icanda's drillers kept the pile plumb, within design tolerances of no more than 6 inches from vertical in 200 feet. The technicians were convinced that this slight deviation could be easily corrected with the special expansible bit used to sink the in-between piles.

At this point Hydro-Quebec, its consulting engineers, and expert panel were faced with a sticky choice typical of construction projects. They had to decide between two methods of sealing the cofferdam. Each had its uncertainties. They could try an ICOS cutoff and hope it could be successfully accomplished to an unprecedented depth. Or they could go for the grout curtain option mentioned earlier, chancing the possibility that the project would be held up for a whole year if the grouting took too long. There was a calculated risk in either case.

The experts unanimously voted for the first option, countering the risk involved with a suggestion that should the ICOS wall fail to plug off the alluvium completely, the leaky section could then be grouted shut. This supplementary grouting was even more feasible in that the geologists predicted that less than 12 per cent of the total cross-sectional area of the wall would be at a depth greater than 150 feet. In other words, the wall would be roughly V-shaped. The risky area would be at the point of the V, and could be grouted shut if necessary. So it was agreed. Hydro-Quebec awarded a contract to Icanda for the cutoff in the upstream cofferdam. At the same time, Soletanche-Rodio signed a contract to install a three-row grout curtain in the downstream cofferdam.

V During the summer of 1961 Manic 5 really began to look like a construction project. The site was changing from one of apparently unrelated activities—explorations, experiments, and preliminary construction—to one of co-ordinated efforts, all aimed at one goal: pouring concrete. While Janin's tunnelers blasted through the west bank diversion tunnels, Oscar Cantin's men built a small city just downstream. By that fall Cantin had built accommodations for 3000 persons, a far cry from the tents and wood stoves of the winter before. And no one-horse town either.

Unlike a suburban community that springs up alongside a central city, using many of the facilities already existing in that city, Manic 5 had to provide everything of its own. It had to have a church, a school, a hospital, a firehouse, a police station, a movie theater, a bowling alley, a grocery store; name it—Hydro-Quebec had to build it. There was no central city, no neighboring town to depend on for anything. And Manic 5 could not grow gradually from a quaint hamlet into a small city. In 1960 there was nothing; by 1962 there would be 3000-plus residents—the men who would pour the 3 million cubic yards of concrete and build the world's highest multiple-arch dam.

But before the first cubic yard of concrete could be poured there was still an awesome amount to be done by the builders. They had to establish a quarry. They had to build a giant crushing and screening plant to process the rock blasted from the quarry into many sizes of aggregate for the concrete; and they had to erect the big sand-classification plant, along with a concrete-batching plant and silos to store the cement coming up the road at the rate of one 35-ton truckload every 15 minutes. Three aerial cableway systems had to span the gorge to place the concrete. These were coming all the way from Switzerland where men had just finished building the highest dam of any type in the world—the 935-foot-high Grand Dixence Dam. A fourth cable suspension system had to be rigged above the gorge to carry a string of 1000-watt mercury-vapor lamps to light the around-the-clock project.

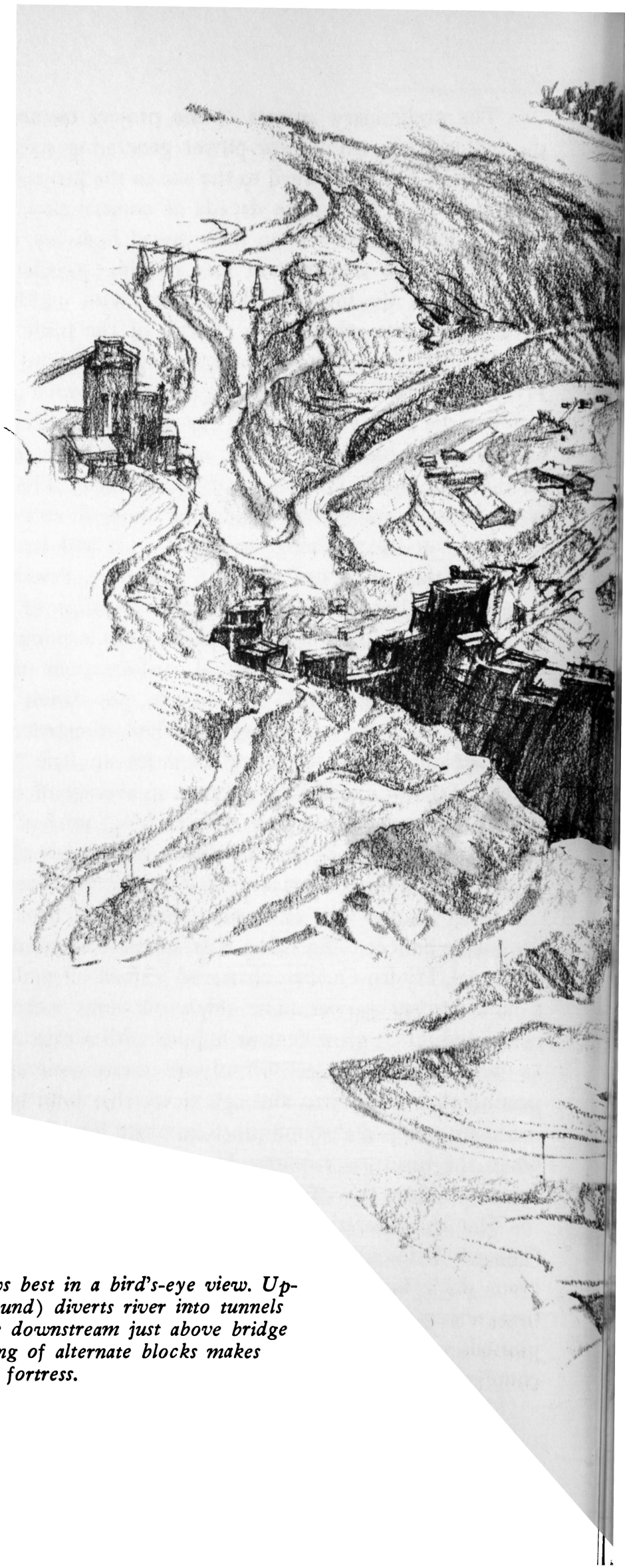
The preliminary aspects of the project seemed endless. Paradoxically, the builders of such a huge power generating station had to run a power transmission line northward to the site so the project and its little city would have electricity during the decade of construction. So, as the road builders put the finishing touches on their gravel highway, linemen built a 115,000-volt wood pole transmission line roughly parallel to the road. Like the road builders, the linemen had to cope with marshland, rock cliffs, raging streams, and the inhospitable climate of the bush.

In order to supply power for the project until this line was completed, Hydro-Quebec brought three huge diesel-powered generating units to Manic 5. Once the road could handle the huge units, each resembling a wheelless diesel railroad locomotive, they were brought to the site and perched high on the west bank, downstream from the dam. The big diesels were also to serve later as emergency generating units should the transmission line be knocked out by lightning or winter's ice and wind.

And then they had to build a seaport. Possibly "seaport" is a slight exaggeration, but nevertheless the transformation of the port of Baie Comeau was a major project in itself. Colonel McCormick had wisely chosen Baie Comeau for its excellent natural harbor, since the production from his paper mills would travel by ship to population centers hundreds, even thousands, of miles away. But the Manic-Outardes development was obviously going to tax the dock facilities at Baie Comeau. Hydro-Quebec estimated that it would have to move an average of 30,000 bags of cement per day through the port, plus thousands of tons of reinforcing steel, giant construction machines, and an almost endless list of supplies and equipment for the \$2-billion undertaking out in the bush country.

The 700,000 tons of cement that would have to go up the road was the major concern. To bring it from the cement mills at Quebec City and Montreal, Hydro-Quebec chartered a small oil tanker and converted it into a bulk cement carrier. The ship's oil tanks were removed and its holds converted into a giant cement hopper with a capacity of 6400 tons. Cement (a word often used erroneously to mean concrete), a powder so finely ground that it can pass through sieves that hold back water, can be pneumatically pumped through pipelines like a liquid. Hence it is handled in bulk when the quantity requires. Hydro-Quebec accordingly commissioned its cement tanker, the *Maplebranch*, to ply the St. Lawrence.

But this operation then required construction of a new dock at Baie Comeau. Once again the Quebecois departed from convention. The concrete dock built at Baie Comeau was designed as both a dock and a breakwater. Its design was unprecedented and written up in engineering journals around the world. The pier's riverward, or weather, side was a concrete wall perforated with large holes which dissipated the energy of



Scope of the project shows best in a bird's-eye view. Upstream cofferdam (foreground) diverts river into tunnels on right bank that emerge downstream just above bridge leading to camp. Concreting of alternate blocks makes the dam look more like a fortress.



the waves (as a breakwater does) while serving also as a structural part of the pier. The somewhat daring design saved both time and money and once more illustrated the Canadians' pioneering spirit.

Since unloading the cement directly into the trucks would require too much layover time for the *Maplebranch*, Hydro-Quebec engineers had to build storage silos at Baie Comeau. Six 1500-ton steel silos were erected near the pier so that the shipboard cement could be fed into a stream of high-pressure air and forced through underground pipelines to the silos at more than 300 tons per hour. The big tank trucks then were filled from the silos. The large semitrailer cement tankers could take on a 35-ton load in four minutes and head up the road to Manic 5.

Meanwhile at the site, work on the cofferdams began. Janin's tunnelers were making good headway and the schedule called for diverting the river into the tunnels in December of 1961. The original jetty built for the experiments was extended out into the river to form the eastern half of the cofferdam. The embankment was made of select fill so as to make installation of the cutoff no more difficult than it would be once it got into the boulder-ridden alluvium. Heavy quarry stone, dumped on the upstream face of the embankment, protected the fill from the river's currents. At the midpoint, about halfway across the river, pile drivers drove steel sheet piles—long flat steel sheets that lock together on their edges—to form a wall of vertical sheeting. When these are sunk in a circle, thus creating a steel cylinder, it is called a "cell." It resembles a big tin can with its ends cut out that is driven into the ground, in this case the riverbed, and then filled with granular material. This sheet-pile cell was installed to keep the outer end of the cofferdam from being washed away by the now pinched-off river.

This initial portion of the cofferdam was not raised to its finished height. The ICOS concrete membrane was only going to extend from bedrock to elevation 685, about 50 feet above the river bottom. From there to the crest elevation of the finished embankment (710 feet) the cofferdam would be sealed by a row of steel sheet piles tied into the concrete membrane. The basic scheme involved beginning the ICOS wall from this first-stage east end of the cofferdam in September, then completing the embankment across the river in December, thus putting the river into the tunnels, and finally installing the western half of the membrane. Icanda's contract called for completion of the cutoff by March of 1962. This would leave just enough time to raise the embankment to its design height before the Manicouagan went into flood in May.

The arrival of Icanda's men at Manic 5 late in the summer of 1961 added true international flavor to a construction project that already had no lack of color and romance. They were young, like most of the French Canadians on the job, but most were already men of the world. Since they

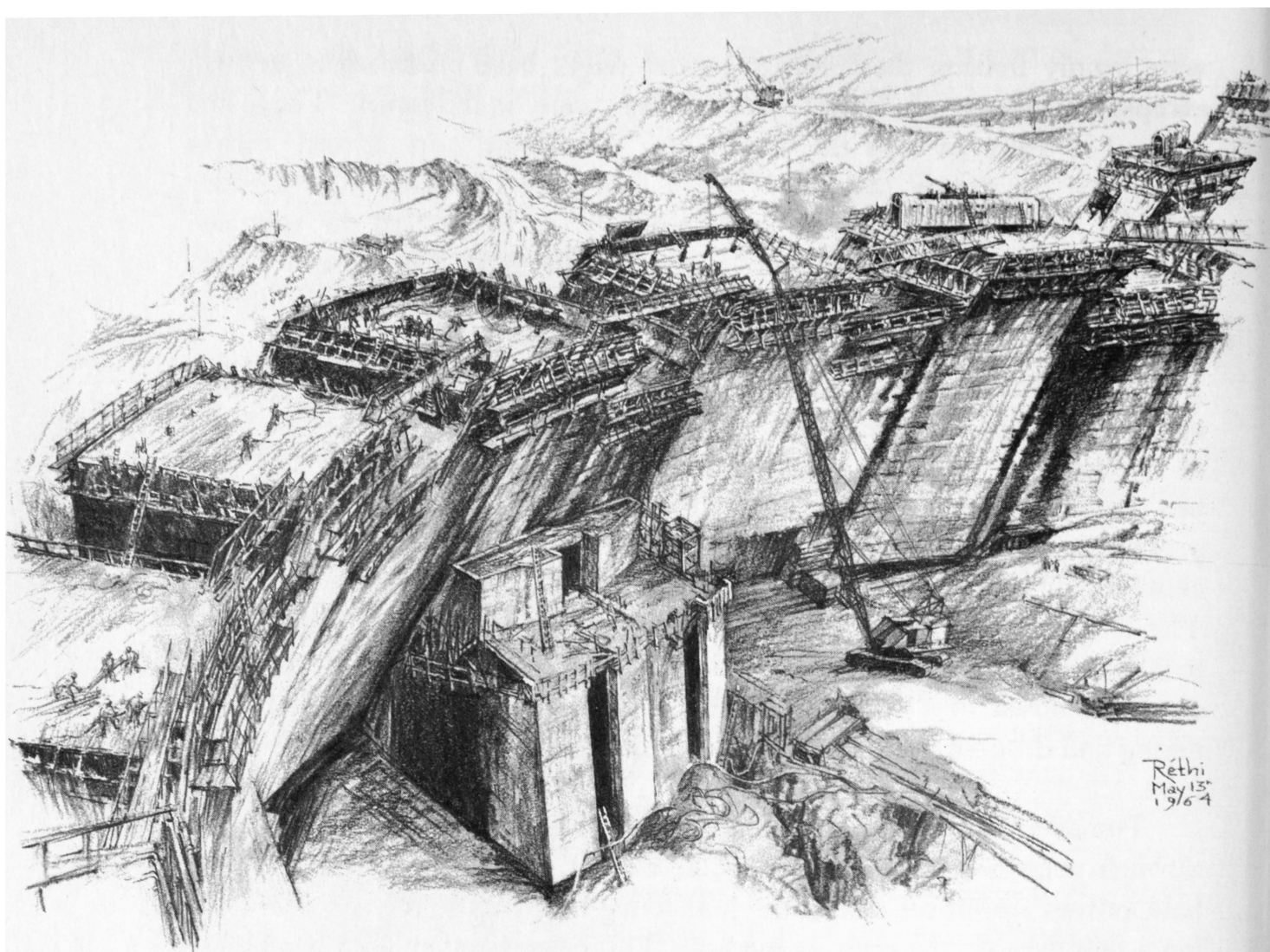
were mainly Italians, the language barrier might have presented a problem except that many of Icanda's technicians were multilingual. They had worked in many parts of the world. In a sense these were artisans with a know-how exclusively their own. They had come to Manic 5 to practice their art, but on a scale never done before. They would seal the upstream cofferdam so that Quebec's dam builders could build the world's largest multiple-arch dam. The Italians added to an esprit de corps that was already high.

Icanda's men began work on the cutoff by installing a kind of template on the surface of the embankment to guide the drillers. The drill rigs, made of tubular steel, resemble baby versions of oil drilling derricks. The drill bits used for a standard hole are like giant chisel blades, with two small perimeter cutters on their outside edges that are at right angles to the main chisel bit. The chisel is suspended by a stem made up of hollow steel sections. This long drill bit (which is lengthened by adding more hollow pipes) is in turn suspended by a cable running to the top of the drill tower over a pulley and back down to a winch. It drills by percussion, the winch alternately raising and dropping the big chisel while an operator slowly rotates the drill stem.

Pumps force bentonite slurry down the hollow stem where it exits through ports near the cutting edge of the bit. The slurry, which fills the hole, presses against the side of the hole filling the voids in the soil and forming a thin cake on the walls of the hole. This cake together with the hydrostatic pressure of the slurry (its specific gravity is slightly higher than that of water) prevents the hole from caving in. Since additional slurry keeps flowing into the bottom of the hole, it creates an upward flow in the hole. This carries the drill cuttings gradually to the surface, where the used slurry with its load of particles overflows into a screen that removes most of the drill cuttings. The slurry is then recirculated.

In the Icanda technique the drillers continue this process until they reach bedrock. (At Manic 5 the holes were extended 2 feet into the sound rock to assure a tight seal between the membrane and bedrock.) Drilling stops when the desired depth is reached, but Icanda continues to circulate the slurry through the drill stem until there are no more cuttings appearing in the return slurry flow.

It is in this drilling phase of the operation that the artisan comes out in the young drillers. Merely by holding his hand on the hollow drill stem as it impacts, an Icanda man can tell what kind of soil he is in. He knows when he is in sand or gravel; he can tell a boulder from solid rock. And as a final check, the underlying geology can always be determined by the nature of the cuttings being removed from the slurry at any given time. Another novelty apparent in watching Icanda's men work, as com-



Workers, performing their appointed chores in alternate monoliths, illustrate the immensity of the main arch. As 1964 season got under way, the outlet control works had been completed. Formwork for galleries that run through the dam are visible on lifts at upper right.

pared with the usual scene on a construction project, is the way one of these skilled technicians will stop what he is doing to pick up a shovel or lend a hand to another worker. He does not wait for a laborer to come do the shoveling; if something needs to be done fast, he does it. The unusual spirit of Icanda's men seems to be "We're here to build a cutoff wall, not to squabble over who does what."

Once this primary hole, as it is called, is pronounced clean, the drill bit is removed and a tremie-concrete pipe is lowered into the hole. The pipe extends to the bottom of the hole, which is still full of slurry. To keep the first concrete that is poured down the tremie pipe from mixing with the slurry, a "she-devil" is put in the pipe first. A semi-inflated basketball is often the she-devil. The ball is forced down the pipe by the weight of the con-

crete to keep the two mixtures separate. It also makes the initial concrete flow down the pipe rather than falling free, which might cause the aggregate and paste in the mixture to separate and weaken the concrete.

When the basketball she-devil pops out at the bottom of the pipe, the concrete begins to fill the hole, displacing the slurry which merely spills out of the top of the hole into a storage reservoir. Keeping the end of the tremie pipe buried in concrete at all times, Icanda's crew slowly withdraws the pipe as the column of concrete rises. In a nutshell, this is the way each element of the ICOS wall is built. A wall is created by installing the next primary element with its center 4 feet away from the adjacent primary element. When the two primary columns have hardened sufficiently, drillers then sink the interlocking secondary element.

Although the ICOS wall is simple in principle, the Manic 5 application was particularly challenging. The completed wall, comprised of a row of interlocking concrete columns, had to be watertight. It was all well and good to begin drilling the primary elements spaced 4 feet apart, but to build a watertight membrane the bottom of the hole more than 200 feet below ground had to be directly below the top of the hole. A row of holes that splayed off in fourteen different directions obviously could never be married into a solid wall of concrete, even with the expansible bit used for the secondary elements.

Icanda's expansible bit could drill the secondary element as wide as 4 feet 6 inches. Theoretically, it should not have to open much wider than 2 feet. But Hydro-Quebec's specifications called for a maximum deviation from vertical of only 6 inches. So Icanda's drill crews took great pains to maintain vertical drill holes. They used the stem of the drilling bit as a kind of plumb line as they went, checking the hollow tube's verticality about every 15 feet. And to be absolutely sure of a hole's direction, Icanda's men used a kind of Paul Bunyan version of the mason's plumb bob, a 600-pound bob suspended from a steel cable. If the giant bob showed a hole going out of plumb, drillers would first try to correct the deviation. If this was impossible, the specifications then required that the hole be backfilled with concrete up to the point where it was vertical. Drilling was then resumed. To build the 286-foot-long wall, Icanda sank 143 piles. This involved drilling approximately 15,000 feet of holes, the deepest one being 252 feet. Of the total footage, Icanda had to fill with concrete and redrill only 330 feet of holes.

Verticality was not the only consideration. The thin concrete membrane had to key 2 feet into sound rock all the way across. To start, Icanda had to make sure that the pile elements were, in fact, founded in rock and not just ending up in a boulder. Every sixth element required the drilling of a small hole with a diamond drill 25 feet farther down into the rock. Further to as-

sure a seal between the concrete membrane and the solid rock, Icanda installed a 2 ½-inch pipe in all the secondary elements, so that after the concrete wall was cast, grout could be pumped down to assure a tight seal between the wall and bedrock.

A further complication was the requirement that reinforcing steel cages be placed in each secondary element. The reinforcing cage was only required in that part of the element where the man-made embankment joined the alluvium. This was specified because engineers were concerned that settling of the embankment might put undue stresses on the thin membrane. Besides having to insure that the wall formed a watertight joint with the rock, Icanda had major problems drilling through the alluvium. At some points, the material being drilled through was extremely pervious. While some portions of the alluvium were homogenous mixtures of silt, sand, and gravel with an occasional boulder, other areas would be highly stratified with big boulders and cobbles nested together into perfect water-bearing formations (the result of a flood in the ancient stream thousands of years before).

Again Icanda's crews showed their craftsmanship. The young Italians varied the slurry mix to meet changing conditions. If the soil absorbed too much slurry, drill crews thickened the mix with more bentonite; or, if necessary, even added cement, sawdust, and straw. Eventually the filler material would clog the stratum that was bleeding off the slurry, and drilling could proceed. Logically, Icanda had the most difficulty in the deep center section of the cutoff. Dynamite had to be used to blast some of the biggest boulders. But by the end of March 1962 Icanda had finished the 2-foot-thick concrete membrane. The river was flowing through the two big diversion tunnels and Hydro-Quebec was ready to begin excavating for the main arch foundations. With this major, albeit preliminary, phase of the work out of the way, the dam builders were nearly ready to start concreting. There was still the excavation of an as-yet-undetermined amount of alluvium from the deep gorge, but the designers back in Montreal had fairly well completed final design of the structure.

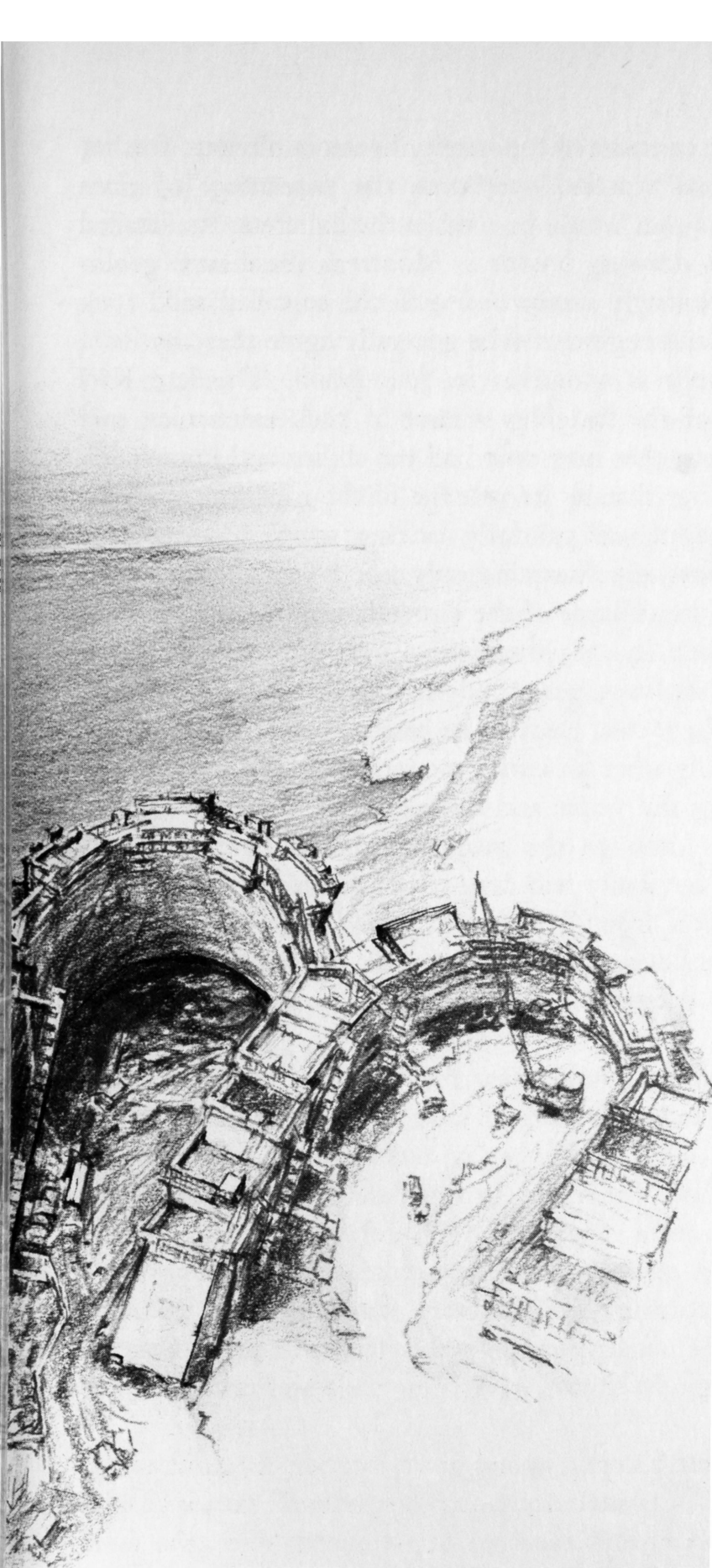
Working directly with Jean Bellier, head of the Paris consulting engineering firm of Coyne & Bellier, SNC engineers now were ready to lay out the complicated foundation excavation for the many arches that would span the gorge. The basic design of Manic 5 followed that of France's Grandval Dam designed by the Paris firm. The arch sections are cut on the downstream side by an inclined plane, which is, in fact, the upstream slope of the massive triangular buttresses. The scalloped upper rim of the series of arches is converted to a straight line by a gravity section, which rests on the vaults of the arches. This gravity crest section transforms the dam's kind of corrugated upstream face into a vertical wall. The downstream face of the dam's crest is a continuation of the buttresses' downstream faces.

VI Although all the multiple-arch dams built up to the time of Manic 5 had been made of similar arches for the total length of the dam, the French and Canadian engineers decided to depart from convention. Because of the difficult topography and the geological formations at Manic 5, the designers elected to use a larger central arch to cross the main river gorge. This led to what is now the most distinctive engineering and architectural aspect of Manic 5—its two huge oblique buttresses on each river bank, where the main arch and the two smaller adjacent arches join. More spectacular, possibly, is that the two oblique buttresses are asymmetrical. The right buttress (dam builders assign right and left sides to a river while facing downstream) reached even farther from the arch's centerline than its left-side counterpart.

These two oblique buttresses consequently distort the symmetry of the two smaller arches next to them, creating two dissimilar, keyhole-shaped configurations. Except for these two arches, all the remaining side arches have spans between the axes of their buttresses of 250 feet. The big central arch measures 530 feet between its buttress axes. The central arch also differs in cross-sectional design from the smaller normal arches. The upstream side of the central arch is defined by a cylinder, while on its downstream side it is defined by an inverted cone. Hence the main arch is much thicker at its base than at its crest.

The normal arches are defined by cylinders both upstream and downstream although their cross-sectional thickness does reduce slightly from about 26 feet at the base to 10 feet at crest level. These dimensions clearly illustrate both the remarkable strength that can be designed into a thin concrete arch and, in a way, the daring engineering involved. Manic 5's central arch holds back a wall of water nearly 600 feet deep, yet is only 87 feet thick at its base and an amazing 16 feet at the top. Calculated stresses in the main and two adjacent arches go as high as 1400 pounds per square inch in some areas. To cope with such great forces, Manic 5's designers had to run complicated computerized studies of the three-dimensional forces that would be exerted on these three arches and their buttresses.





Topography and geology of the gorge cause design engineers to place central arch's buttresses asymmetrically to others, creating a unique keyhole configuration in its immediate neighbor to the east.

Here again the need for concrete of top quality becomes obvious, further demonstrating why geologists worried over even the percentage of mica particles in the grains of sand that would be used in the concrete. As detailed plans began to come off the drawing boards in Montreal, these same geologists at the site became increasingly concerned with the so-called solid rock under their feet. Geologists and engineers alike generally agree that any dam, in fact any structure, is only as sound as its foundation. The late Karl Terzhagi, considered dean of the fledgling science of rock mechanics, said shortly before he died in 1963 that man now had the ability and knowledge to build a dam a mile high but that his knowledge of the rock on which he would have to found this dam was painfully lacking.

This fact had been disastrously illustrated only a few years before when a foundation failure caused the collapse of the concrete arch Malpasset Dam in France. But on the plus side, in 1963 the highest arch dam ever built, the 860-foot-high Vaiont Dam in Italy, withstood an unprecedented test of its strength. The towering arch, 76 feet thick at its base and only 12 feet thick at its crest, remained standing after an entire mountainside slid into its reservoir, completely displacing the water and wiping out a village of several thousand just downstream. Although the geologists should have predicted the potential landslide, they obviously had done their job on the dam's foundations, and the dam designers around the world sighed with relief even in the shadow of disaster. Confidence in concrete arch dams was bolstered, although the memories of Malpasset and Vaiont still hang heavy in the minds of dam designers.

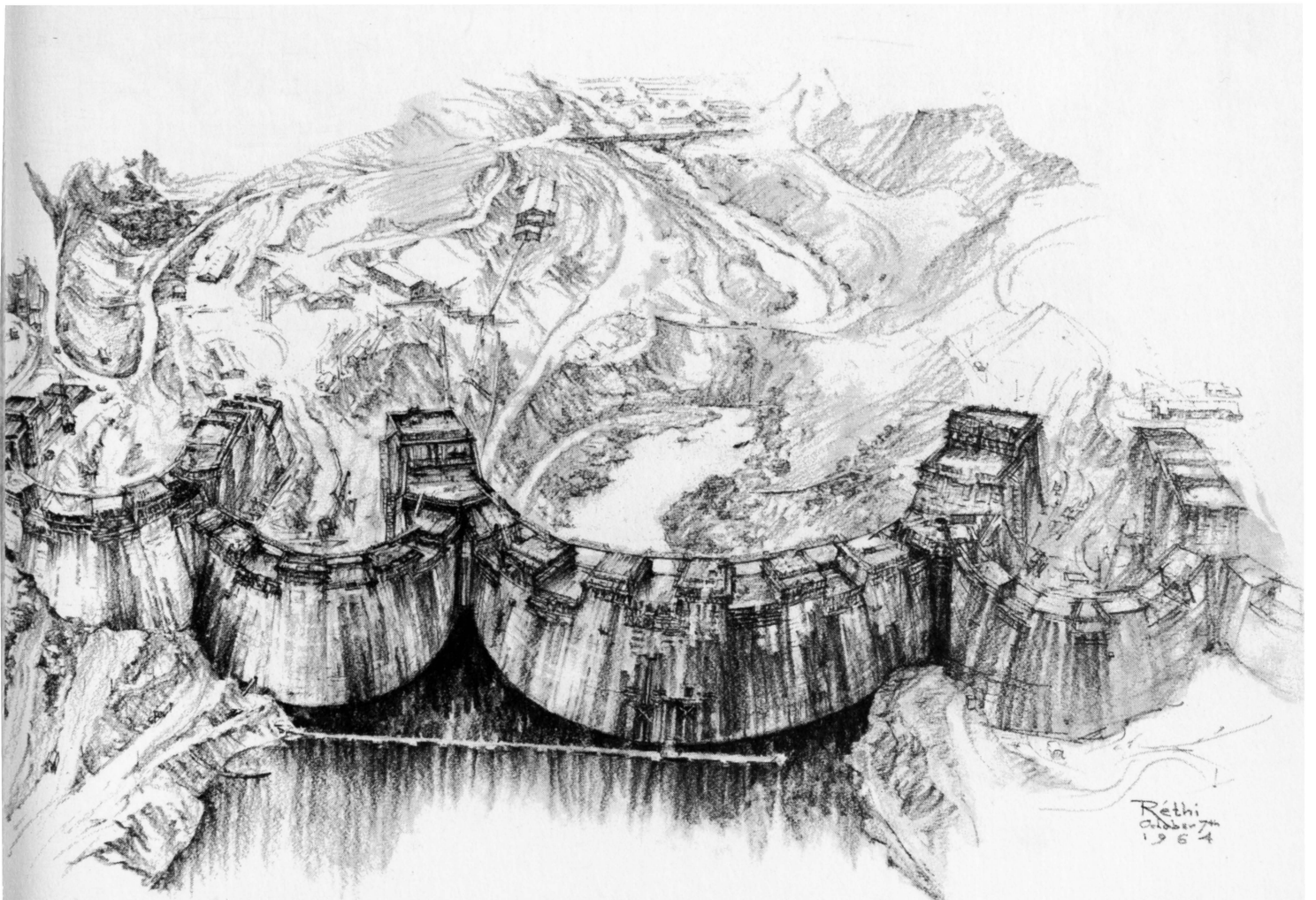
The computers in Montreal could spew forth endless assurances that Manic 5's arches and buttresses would do their jobs. But it remained up to the personal judgment of the geologists whether or not the rock below would support the concrete structure. These men had to base their calculations on certain assumptions that in turn were based on other assumptions. The engineers designing the man-made concrete structure were working with known quantities. The performance of concrete, assuming it is made to exacting specifications, can be accurately computed. It can be proved out in laboratory tests. Hydraulic model studies have been made and proven in the field.

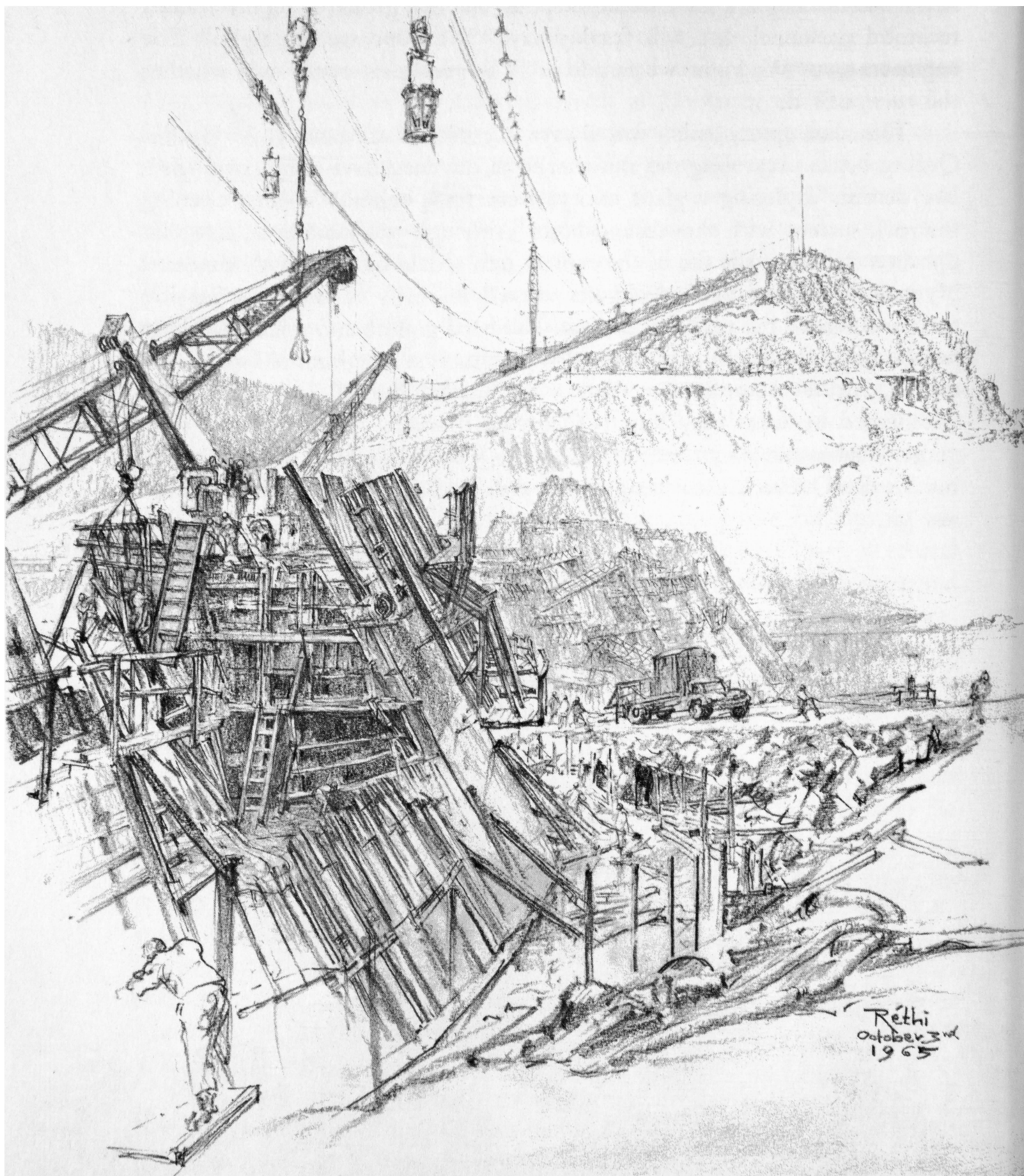
But the geology of the earth's crust in any given location is an unknown. Rock can be probed with drills, tunneled and dug into, but still man is limited in his investigation. There is always the area between the holes; the fault that can parallel the drill hole 5 feet away; the seam that can be dangerously lubricated with a thin lens of slippery clay, except just where the drill passed through; and the supposedly impervious formation that can become pervious when subjected to the tremendous hydrostatic pressures exerted by a reservoir 600 feet deep. On any big dam project, it is only the geologists who

never boast. They are the chronic skeptics—the one group of highly trained technical personnel that will frankly say, “We *hope* we are right.” The engineers say, “We know we can do it.” The geologists worry over whether the *rock* will do it.

This same apprehension was always in evidence at Manic 5. As Hydro-Quebec began excavating the alluvium from the deep river gorge, geologists, like dentists exploring a giant cavity, were right behind the men cleaning the rock surface with shovels and hoses. Although this mammoth, irregular slot directly below the site of the central arch would be filled with concrete, Hydro-Quebec and SNC geologists wanted to verify as nearly as possible their analyses of the rock formations. The hard granite and gneiss had been polished and shaped by the rushing waters so that in places it looked like marble, further complicating these examinations. But all concerned were encouraged by what they found—all except the men digging out the deep gorge. The sound rock walls of the gorge were good news for geologists, but Hydro-Quebec’s excavating crews were finding what seemed a bottomless pit.

View from upstream late in 1964 construction season shows downstream cofferdam still in place, the upstream structure long since submerged. Smaller arches on either side of main arch rise at approximately the same rate.





From the west across gorge, the inclined ramp for the cableway tail towers is still a pronounced landmark, but record concrete production during 1965 season raises dam to impressive proportions. Worker in foreground prepares formwork for easternmost arch.

Power shovels did the work at first, loading the gravel, sand, and boulders into trucks, which whined up steep roads leading out of the slot. But as the gorge narrowed, the excavators and their machines began to get in each other's way. There were the predictable jokes about switching to teaspoons and hauling the alluvium out of the hole in workers' pockets, but before the slot was completely cleaned out these jokes had become quite unfunny. By the time Hydro-Quebec reached bottom, its crews were using picks and shovels, hand-loading small skips (metal boxes) that were then hauled up out of the hole by small cranes perched up where the gorge widened.

Work proceeded in the dry, thanks to the unqualified success of the ICOS membrane in the upstream cofferdam. Water infiltration was negligible and most seepage was handled by two 1000-gallon-per-minute submersible pumps installed in two 24-inch-diameter wells drilled near the downstream toe of the big cofferdam. And just as well, since Hydro-Quebec's excavation crews were now bottoming out about 175 feet below the riverbed. They had removed 400,000 cubic yards of alluvium and were standing in a narrow slot more than 200 feet below the river's water, backed up by the cofferdam.

As these men labored in the bowels of the Manicouagan gorge, others worked nearly 1000 feet over their heads. In fact, the gorge was a beehive of activity from top to bottom. The real high-altitude operation was the installation of the aerial cableways. Often referred to by dam builders as a "highline," a cableway system used in construction can best be described as a highly sophisticated, gargantuan version of mother's pulley clothesline.

Mechanically, the system resembles the tramways or cablecars common to ski areas in the Swiss Alps. A construction cableway, of course, has no passenger-carrying cars. Its primary job is to carry buckets of concrete or whatever else the construction man decides to hang on the hook. Spanning the gorge is a main supporting cable, often called the "gutline." This steel cable is 3 inches in diameter, about 3700 feet long and specially designed for the particularly punishing job it has to do. The gutline is stationary, secured at each end, although, as at Manic 5, one end is usually fastened to a mobile tower that moves in a slight arc, thus describing a larger triangular area of operation on the ground.

Riding on the gutline is a many-wheeled trolley, called a "carriage," which moves back and forth across it. A set of pulleys and cables rigged to a giant winch controls the horizontal travel of the carriage. A completely separate system of pulleys and cables does the hoisting, raising, and lowering of the two-part pulley block that actually carries the hook and whatever load is attached.

At Manic 5 there were three cableways, most of the major components

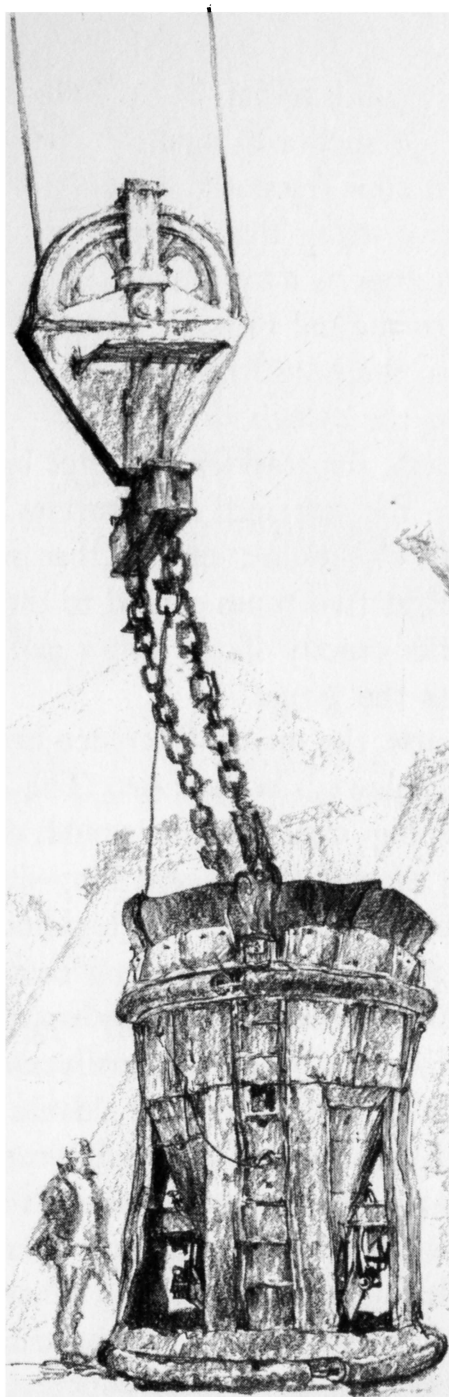
of which were brought over from Switzerland where they had been used to build Grand Dixence Dam. These units were another of the anomalies of Manic 5—an Italian company had built the machinery originally and all the control dials and operating instructions were printed in Italian. A French Canadian at the controls in an operator's cab following radioed instructions in Quebecois French and manipulating levers and dials marked in Italian was a humorously cosmopolitan aspect of the project.

Manic 5's cableway systems were different from those at Grand Dixence, although the same winches and other equipment were used. Unlike the usual alpine damsite, Manic 5 did not have a steep cliff on each side of the river. On the west bank, a high ridge rises sharply, an ideal anchorage for one end of a cableway. But the east bank, although steep, goes up more gradually. Because of this, the more or less horizontal gutlines would have had to extend more than a mile to span the gorge at the proper elevation. To cope with this situation, Hydro-Quebec crews braved 40-below-zero temperatures to erect three steel head towers on the east bank. These head towers resemble extremely heavy-duty radio antennas, although they were not as high as most radio transmitter towers. But the big towers, each 376 feet tall, were perched high on the east bank mountainside so that their tops were nearly even with the peak on the west side.

The three heavy gutlines extended from anchorages on the ground, over the tops of the head towers, then across the gorge about 3700 feet to the mobile tail towers on the west side. While crews erected the high steel towers on the east side, blasters carved two curved shelves from the mountain on the west bank. These shelves, hewn from the rock, were to carry the curved tracks on which the mobile towers ride. The steel rails were bolted to concrete ramps cast on the rock shelves. One tail tower, which could move the farthest upstream, rode a horizontal ramp located at elevation 1310, just over 100 feet above the crest height of the finished dam. The other two tail towers rode a second ramp, an inclined structure that started at elevation 1202 and about in line with the dam's axis. This ramp, a landmark of the project until the dam stole the limelight, climbed upward on a 37-degree incline to the very peak of the mountain at elevation 1495, nearly 1000 feet higher than the bottom of the gorge where the first bucket of concrete would be poured.

The tail towers at Manic 5 were not towers in the true sense of the word. They were actually squat structures, best described as counterweighted A-frames. In an A-frame the legs of the A ride rails similar to railroad rails except that they are more widely spaced and are bolted to the concrete foundation ramp. The steel A-frame straddles a massive concrete lip that is a part of the ramp. A third rail bolted to the back side of this lip is the rail on which the tower's traction drive works. This rail also serves to prevent

This battered veteran of a bucket holds 8 cubic yards of concrete that weighs 16 tons. Three buckets like this placed more than 5000 cubic yards in one day during peak concreting year of 1965.



*Rethi
Concrete
1965*

the tower from being pulled off the ramp, much as the flange on a railroad wheel keeps the wheel on the rail. A small electric motor, working through a gear system, drives the tower back and forth on its rails.

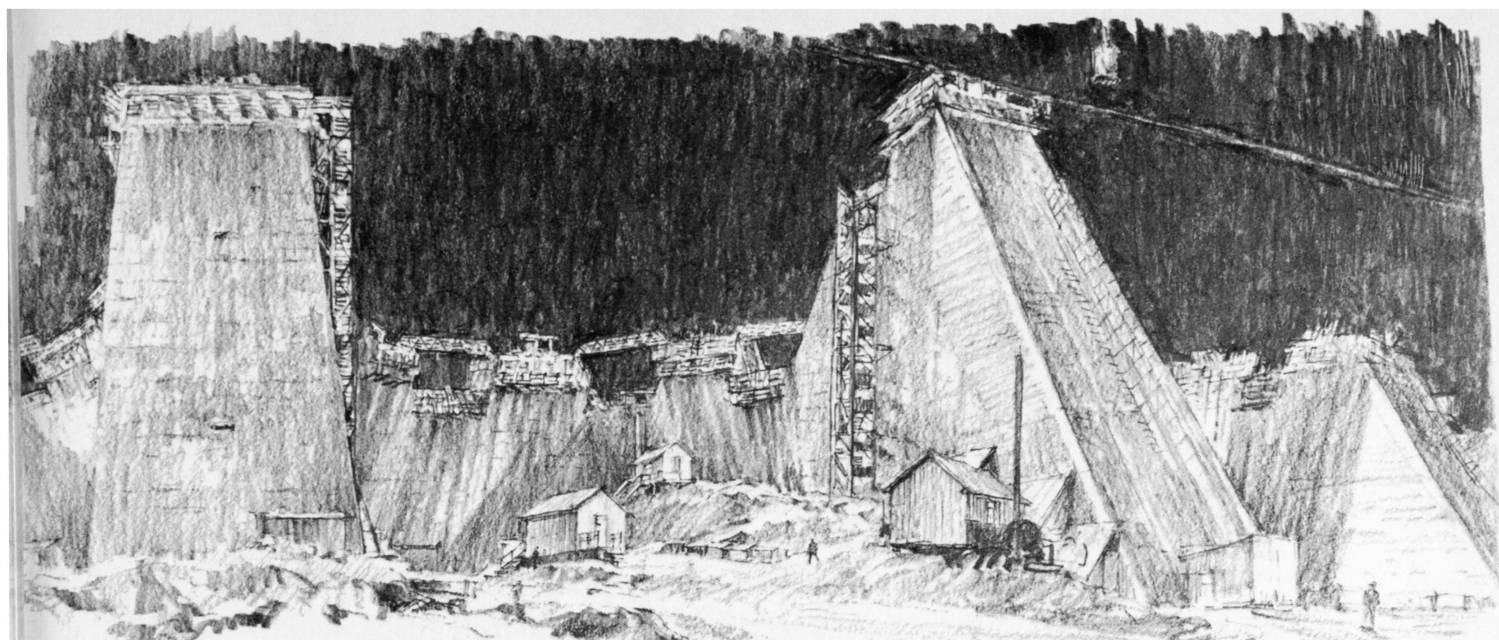
A cableway tail tower serves three purposes. It anchors one end of the fixed gutline. It anchors the fixed end of the hoisting line that runs from the tail tower out to a pulley on the carriage, down to a pulley block that carries the hook, back up to a second pulley on the carriage, then across to the top of the head tower, and, finally, down to a huge winch on the ground. At Manic 5 this hoisting line was a 1 3/8-inch-diameter "wire rope" (the technical name for steel cable).

Its third job is to handle the pulley of the traveler line, a slightly smaller wire rope $1\frac{1}{4}$ inches in diameter. This line controls travel of the carriage. The traveler rope traces the most complicated pulley system of the cableway. Like the tiny string that moves the horizontal dial-indicator on radio sets, the traveler rope is a continuous line. It starts on one side of the carriage, runs back to the tail tower, through a pulley, then all the way back across the gorge to the head tower, down to the winch on the ground. But it does not end on the winch drum. After making a series of turns around the grooved drum, the traveler line runs back up the head tower, over a pulley and back to the carriage. The traveler pulley system most closely resembles the familiar clothesline, except that instead of ending at the top of the head tower, its two ropes extend to the ground and wrap around the winch, which works exactly like a ship's capstan, to move the carriage back and forth across the gorge.

Of course, the major difference between mother's pulley clothesline and Manic 5's cableways is their size. The cableways were built to carry 25-ton loads. One big steel bucket would carry 16 tons of concrete, so every component of the system was king-size—pulleys 4 feet in diameter, winch drums 6 feet in diameter. The highlines at Manic 5 were big because they had a big job to do—transporting nearly 3 million cubic yards of concrete.

One of the most fascinating aspects of a cableway is that the operator in his small control booth is usually completely remote from the work that his machine is performing. At Manic 5 the three operators' booths were placed high on the left bank, downstream of the dam's axis and slightly lower than the head towers' bases. Although the operators got a magnificent view of the over-all project, they nevertheless were not allowed to operate visually. Other men were spotted wherever the highline was to work, using small portable radios to direct the cableway operators. In fact, as soon as the cableways began to pour concrete, the operators became "blind." The big concrete loading dock, where concrete was dumped into the cableway buckets, was built farther down the craggy slope out of the operators' line of vision.

A man with a radio directed the bucket into the loading dock and sent it on its way when it was filled with concrete. Once the bucket was airborne, the operator had a degree of independence. Having been guided carefully by radio with his first bucket of concrete, the operator could see from his controls that he had moved his tail tower (which he controlled remotely) so many feet upstream. Other dials showed him that he moved the traveling carriage so many feet across the gorge and a third dial showed him how far down the hoisting line had gone. By noting these three readings, the operator could return the bucket to the same general location repeatedly, but the radiomen always took over for the final positioning.



Réthi
September
1965

More than eighty 1000-watt floodlights, strung overhead on a fourth cableway, keep the dam in eternal daylight. Workers boast that you can read a newspaper atop the dam at night.

Besides the building of the three cableways to handle concrete, there was a fourth bit of daredevil engineering to be done. Manic 5's construction was like most hydroelectric projects—once the decision is made to build, the project is pushed as rapidly as possible. One obvious reason for haste is that there is no return on such a capital investment until the plant is generating power (power revenues are generally used to amortize the bonds sold to finance construction). Moreover, in the case of Hydro-Quebec, Manic 5's power would be needed by the early 1970s.

As Manic 5 would be an around-the-clock construction project, the vast site had to be illuminated at night. So Hydro-Quebec decided on a fourth highline spanning the gorge. Two guyed towers, one 400 feet high on the east side and the other 250 feet high on the west mountaintop, supported the 4000-foot-long light line. Even this setup required a system of pulleys and wire rope so that the string of 1000-watt mercury-vapor lamps could be reeled in for servicing and replacement of elements.

Although the project's location, roughly 51 degrees north latitude, made for long days in the summer (sunrise about 3:30 A.M., sunset about 10:00 P.M.), the winter days were just the opposite. By midafternoon in the fall and early spring, the big lights would come on and flood the gorge with artificial sunshine. And they stayed lighted until well after breakfast every morning. Once construction started at Manic 5, lighting was continuous except for shutdowns on Sundays and, of course, the three- to four-month winter shutdown each year.

Actual construction did not begin on the dam until the 1962 season. But a lot of so-called preliminary construction was completed before the dam's first concrete was poured. Seven miles from the damsite proper a sand-classification plant had to be finished, which was a major project in itself. The \$1-million, completely automated plant was every bit as complicated as many industrial processing plants. The puzzling aspect to the uninitiated was the process. Sand went into the plant, was put through a highly sophisticated classification system, and the end product spewed out the other end—to the untrained eye, just more sand. But later we shall see how and why this sand was so carefully processed. It was a key component of the concrete.

There was another major processing plant that had to be built. The Manic 5 concrete plant, when it began operating full blast, would consume nearly 10,000 tons of coarse aggregate, crushed rock blasted from the quarry just over the ridge high above on the east bank. The aggregate plant was actually a sprawling complex of rock crushers, screening and washing plants, conveyor belts and huge stockpiles. This aggregate operation had to maintain a continuous supply of the many different sizes of crushed rock, ranging from 6 inches down to the finest aggregate, the sand that was trucked in from the classification plant and incorporated into the main aggregate operation.

The big concrete plant itself, a nine-story structure perched on the east bank just a bit below the aggregate complex, was the focus of all this other activity. When complete, all the various processing operations would feed the concrete batching operation, or "batch plant." Two big cement storage silos were built right next to the batch plant, each with a capacity of 9000 tons. The never-ending convoy of trucks coming up the road from Baie Comeau would keep them filled. Conveyors from the aggregate plant led to the top of the big batch plant to keep its bins filled with crushed rock and sand. Compressed air forced cement from the silos to the top of the plant. An oil-fired boiler house on the east bank was built to supply steam for heating and various other purposes. And probably the most unlikely part of the whole mammoth complex, clinging to the steep hillside, was the ice plant.

Although one automatically thinks cold when thinking of Manic 5, concrete specialists think heat, regardless of climate. When concrete is made from the mixture of cement, water, sand, and crushed rock, a chemical reaction takes place between the cement and the water which generates heat—heat of hydration. The larger the mass of concrete, such as that in a dam, the longer this reaction, called "curing," takes. The heat of hydration does not dissipate fast and consequently the rock-like mass will remain warm for a long period. Thermocouples will give readings of 100 degrees and higher in curing concrete, and heat continues to be generated sometimes for years. Like most other substances, concrete shrinks as it cools. And this shrinkage is what concerns the dam builders. They must know the precise size of each block,

or monolith, of concrete in a dam. Since it would be impossible and, in fact, undesirable to build a dam as a continuous monolith of concrete, there are necessarily vertical construction joints. These joints must be watertight, of course, when the dam is finished, so the orderly contraction of the individual concrete blocks is essential.

Engineers, therefore, carefully control the temperature of the concrete from the batch plant all the way through to the finished structure. Hence Manic 5's builders had to have a refrigeration plant capable of making 250 tons of shaved ice per day. The batch plant controlled the temperature of the mix two ways. During warm weather, above 50 or 60 degrees, some of the water in the mix was replaced with shaved ice. Special low-heat cement was also used, which stretched out curing time to ninety days (normal cement cures in about a month) but helped to hold down the heat of hydration. In the large lifts at the base of the dam, Manic 5's engineers imbedded aluminum and later steel tubing in the concrete. Once the lift was poured, cold water from the river was pumped through these tubes to help draw off the heat and expedite curing.

Taken individually, none of these aspects of the big concrete manufacturing complex are particularly unusual. But collectively, they represented a mammoth operation. To perform it, Hydro-Quebec had to bring 3000 persons into the bush. And to do that, Hydro-Quebec had to build accommodations for them. In order to build the dam on the Manicouagan, there had to evolve a place called "Manicouagan." And it did.

VII By 1962 an airline traveler in New York City could walk up to the Air Canada ticket counter and say “Manicouagan.” Instead of registering a blank look, the ticket clerk dutifully wrote the destination code “YMV” on your ticket. Your bag was tagged for “YMV,” and you were on your way to a small city almost 1000 miles away that had not existed three years before.

Manicouagan was now on the map. At least it was on some maps—the more recent ones and those that included the northern part of Quebec. True, the main street was only a gravel road, but a very well maintained gravel road with fewer bumps than most paved roads. And the buildings were kind of look-alike, mostly all the same shape and covered with the same utilitarian galvanized sheet metal.

There were no tall buildings. The concrete batch plant across the river was probably the tallest building around, but it really did not count as part of the town. The firehouse, although similar to most of the other camp buildings, did have a hose-drying tower, maybe three stories high. And the church had a steeple, not very impressive, but still a steeple. There were no vine-covered cottages at Manicouagan either, but some of the big house trailers up at Lac Louise were very comfortable inside. (The climate did not lend itself to vines on the outside.)

Despite its drabness, the little city of Manicouagan was a far more complete community than many of the suburban towns that cluster around the large urban centers like Montreal and New York. Aside from the basic feeling of isolation, the residents of “the camp,” as they called it, had most all of the amenities of civilization. Because of the isolation, Hydro-Quebec went out of its way to make the place livable.

Naturally, there had to be the usual fundamentals—a police station and jail, firehouse, school, mess hall, bank, post office, hospital, and church. But there was also a tavern, a movie house, a bowling alley, a billiard hall, a big sports arena, and a kind of restaurant-general store. The latter was one of the more fascinating facilities on the project. In the English sense, the name “restaurant” really did not apply. There were no tables and chairs, no

waiters. But in the French sense, and after all the word is French, Manic's restaurant was indeed a place to eat. It was set up as a stand-up snack bar, but there was a daily menu and complete meals were always available.

The restaurant was also the general store. It was the central gathering place for the camp. Besides coming there for a snack or a meal, workers bought cigarettes, tobacco, magazines, newspapers, and, in a separate section of the building, just about anything else they might need. A Manic 5 worker could buy anything from a suit of long underwear to the latest model stereo tape deck at the so-called restaurant.

To handle this type of operation on its construction projects, Hydro-Quebec contracts with concessionaires. Les Comptoirs Forestiers du Quebec, Incorporated, known as "CFQ," ran the restaurant, the tavern, a private club for foremen and higher echelons, and the gas station and service garage. Charles Rosset, CFQ's director at Manic 5 for several years, said proudly: "Anything you find in Baie Comeau or other comparable towns, we have here. Most people are surprised. They somehow expect to find us living in a tent, or some dilapidated hut with merchandise three or four years behind the times."

Actually, the situation was just the opposite. A large majority of the workers at Manic 5 came to the project to work because it was a big town compared to the small towns and villages where they lived. Manic 5 had everything: besides all the routine facilities, for young people there was always something to do. There was the day-and-night ski tow, the ice skating rink, movies, bowling, baseball. Name it, there was always something going on at Manic 5, which was more than you could say for the old home town. And a more than interesting aspect of the project, although few girls would admit it, was the twenty-to-one ratio of men to women in the camp proper. Most workers, including the girls, said the biggest reason for coming to Manic 5 was the money. In general the pay was better than they would have gotten at home.

Rosset discussed his own employees: "The service station, the groceries, the taverns are staffed mainly by people we've hired in the Saguenay, Chicoutimi, the Lake St. John areas, around Gaspé and Matane. Although we hire most of our managers through personal contact, the clerks and others on the selling floor are mostly hired through employment and other agencies of the government."

The same was true for Hydro-Quebec itself, by far the largest employer on the project. A large percentage of the construction workers at Manic 5 came from the counties nearest to the project. According to André Payer, head of personnel relations on the project in 1967, "The farther you go from Manic 5, the smaller the percentage of the total labor market that we hire. In the surrounding counties we may hire about 7 or 8 per cent of the total

market; but, in Montreal, for example, we might take less than 1 per cent of the total labor market.”

Although getting men and women to go out into the bush to work might seem difficult, it is a fact of life with many Canadians. Canada's area is second only to the Soviet Union, yet she had a population that only topped 20 million in the 1960s. Most of these people are clustered along the Canadian-United States border, particularly in the Montreal-Quebec-Toronto-Vancouver regions. In fact, most of Canada can be categorized as remote, and Canadians, especially construction men, are accustomed to working far from civilization. North America's early-warning radar installations, strung across northern Canada, took the nation's construction men unprecedented distances north of the population centers. And since World War II Canada has pushed out into the north country, developing its vast wealth of natural resources. Nor are the pioneers who have done the pushing all bulldozer operators; they are from all walks of life.

A good example is Fernand Imbeault, executive chef at Manic 5 during the last five or six years of construction. He could easily double as the *maître d'hôtel* at New York City's Waldorf-Astoria. Tall and distinguished, wavy hair with just the right amount of silver, and that look of “Sir, I should be able to have a nice table for you in about five dollars.” But Imbeault was at Manic 5, responsible for feeding 3000 persons a day in a huge cafeteria.

Practicing his art in the bush did not faze Imbeault: “I did it in the arctic, on the DEW line. In Montreal I was a restaurant *maître d'* and the manager of a big cafeteria. I know how to operate a bar or a banquet.” He began his career as a camp cook when he was fourteen years old. “At fifteen I was already in charge of a small kitchen.” And in one way things had not changed much: Imbeault's work force of more than 200 at Manic 5 consisted mainly of youthful types, boys and girls ranging from sixteen to twenty-one years.

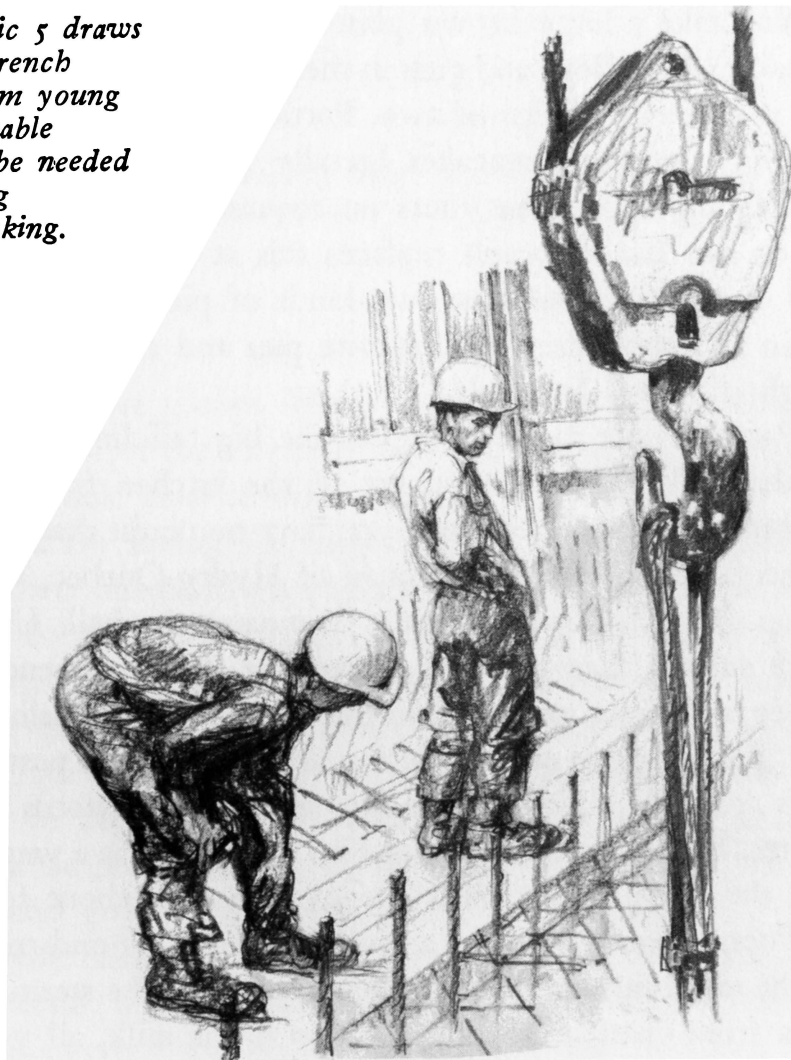
Imbeault's operation at the remote construction site illustrates another advantage that attracts young Canadians to the north country. “When I first arrived here, we used to hire cooks from Montreal,” said Imbeault. “Well, I am not a drinker myself, I only take a drink socially. It's seldom you see a chef that doesn't drink, but I am one of them,” he said with a grin. “The ones we used to get from Montreal were drinkers. In the morning (we start at 4:30) we would be missing maybe four or five second cooks. This was no joke. One morning I got mad and fired five of them.”

Imbeault decided to develop his own cooks from the personnel he had at Manic 5. “So, we took young fellows and we built them up, little by little. By 1966, there were none left from the outside. All our cooks had learned their trades at Manic 5.” As an example of the success of his on-the-job train-

ing program, Imbeault said, "We had some fellows who worked for the company eight or nine years, starting out as just a third cook. Now one of them is my first assistant. He's happy and he's a good cook, I'm telling you, as good as anyone I've known."

Fernand Imbeault was probably as important to the construction of Manic 5 as its top engineers. He tried to imbue his staff with this credo: "It doesn't matter if you're a kitchen worker or a dam worker. You both work for the dam. Our business is to serve the men who build the dam." And a formidable assignment it was: feed 2700 men a day and keep them happy. Like soldiers, construction workers run on their bellies; and like the proverbial housewife, Imbeault's day was never done. Since the project ran around the clock, providing each worker with three meals a day meant serving four meals. Workers on the day shift started at 7:00 A.M., took an hour to eat between 12:00 and 1:00 P.M., then worked until 6:00 P.M. The night shift ran from 7:00 P.M. to 6:00 A.M., with an eating hour between midnight and 1:00 A.M.

Construction of Manic 5 draws men from all over French Canada, many of them young men who gain invaluable experience that will be needed for Quebec's next big hydroelectric undertaking.



Here is a profile of a typical day for the chef during the height of construction:

He is up at 4:30 A.M., along with a contingent of kitchen workers. The upper portion of the dam, which looms over the camp, is shrouded in heavy fog. The early morning air is crisp regardless of the time of year. The cafeteria begins serving at 5:30. Workers and supervisors, both male and female, begin their assault on the big galvanized metal building with its plumes of steam and smoke. They come from all parts of the camp, some on foot, others in cars and trucks.

Some workers come off the dam, their rugged clothes and faces dirty from the night's work. The clean but sleepy faces are day-shifters. Seven o'clock means work for these men, but seven is also important to the night workers. The tavern opens soon and there's nothing like a cold bottle of Labatts ale after a night's work.

The diners file down the central aisle of the cafeteria. A young boy at a desk meticulously checks each person's identity. Workers pay \$11.65 a week for dining privileges and only those who have paid are fed. Otherwise the arrangement is a standard cafeteria arrangement, grimly reminiscent of an army mess hall.

You take a large brown plastic tray and silverware, then move along the steam tables. Boys and girls in their late teens dish up the main course and there is always a choice of two. Portions are generous. An order of bacon with your morning pancakes literally smothers two large pancakes. The youth frying eggs turns yours on request. Fruit, either canned or fresh is next on the line. Imbeault replaces this at dinner (the noon and midnight meal) with dessert—at least two kinds of pie made fresh the night before. "Raisin and apple are their favorite pies and chocolate cake they can't get enough of," says Imbeault.

Partitions are suspended from the big building's bare steel roof rafters in order to keep the atmosphere of the kitchen from reaching the dining area, but with your eyes closed you have no doubt that you are in a cafeteria. On this partition the official shield of Hydro-Quebec, with a big beaver on the top (the first dam builder), dominates the hall. Under it is a crucifix (much smaller than the beaver, but the strong presence of the church in Quebec is obvious, even deep in the bush country). Below the crucifix is the menu. Flanking this central display are the standard posters seen everywhere in this country: a picture of a fireman—then the words GARE AU FEU, SAUVE DES VIES. Prevent fire, save lives. Fire prevention is a way of life in the bush. Even the inside of a cigarette package warns about forest fires.

Popular music, usually a kind of tame rock-and-roll, fills the cafeteria and the street outside. Diners reach the end of the steam tables taking coffee or tea from giant urns. The last stop is for milk, all you want, and many



Youthful kitchen worker is typical of those who venture deep into the bush to build Manic 5. He does not work in concrete, but helps to feed the men who do.

workers take two and three glasses. There is a sort of auxiliary table at this point with jelly and jam for the morning toast and pickles and other relishes like pickled beets or cole slaw at other meals.

Diners mingle at the tables. An engineer, bulldozer operator, and two cute young nurses share one table. As might be expected, construction workers eat voraciously. Some trays are loaded as though for three men: a double order of pork chops, three scoops of potatoes, two glasses of milk, two cups of coffee and, depending on the flavor, at least one wedge of pie. Of the men's appetites Imbeault says, "It's a shame. But what can you do? I think if we could speak to them alone, to make them understand that if they would only take what they need, it would make it so simple for me to balance my costs and give them a better menu for the week.

"I write the menu once a week. It is approved by Mr. St. Pierre [H. H. St. Pierre was director and general manager for Cordiner, Hubert and Bond, the Montreal caterers that had the food concession at Manic 5] and

signed by Hydro-Quebec. And I only have so much to work with. The guys don't realize that. I get these gray hairs for some damned good reasons," says Imbeault.

Despite the around-the-clock operations on the dam, Imbeault fed the camp with dispatch. For the noon meal and the so-called midnight dinner the menu was the same. The staff ate from ten to eleven o'clock, then meals were served until one. Supper and breakfast time was roughly five-thirty to seven.

Besides the main cafeteria, Imbeault had two field kitchens, one up near the dam on the east bank, the other at G-13, the sand plant 7 miles away. These remote kitchens were for workers who did not have the time or the urge to make the trip down to the camp for the noon meal or the midnight dinner. "All that food was prepared here and transported," said the chef. "We feed approximately 350 men at one of those in about eleven to twelve minutes. Quarter after twelve the dinner is already over. Some of them already are lying down."

Chef Imbeault's job was not limited to Manic 5, either. "We had the milk factory here, too," he said. (Manic 5's milk factory was just that: a small room where powdered milk is reconstituted to liquid remarkably like the real thing. I found many workers unaware they were drinking powdered milk. "We made 1200 gallons a day." This took care of Manic 5 plus two other projects south of Manic 5, the big Outardes 3 and Outardes 4 hydroelectric developments, also being built by Hydro-Quebec. "I called in for their orders every morning and then we made up whatever they needed. It went down to those jobs by truck."

Fresh fruit and vegetables came to Manic 5 once a week. Imbeault ordered these supplies every Monday from Montreal and refrigerated trailer trucks arrived on Thursday. A refrigerated building, marked LÉGUMES, stored the fruits and vegetables until used. Meat and eggs came the same way once a week. "We used 350 dozen eggs for breakfast," said Imbeault. "You get seven grills open with seven cooks frying eggs in the morning from five-fifteen until seven. People don't believe it, but it's a fact." Depending on the kind of pie, Imbeault's bakers made up to 850 pies for one meal.

Cordiner, Hubert and Bond employed 245 persons at Manic 5. This included bakers, butchers, pastry men, the milk factory man, dishwashers, kitchen workers, and banquet specialists. All but twenty-three—maids and janitors who cared for the workers' living quarters—worked for Imbeault.

Did the men at Manic 5 have a favorite meal? "Oh, my God—chicken!" said the chef. When the meal was chicken, for example chicken legs, he prepared 4300 orders to feed the 2700 diners. "When I first started here, I made pizza. Well, my God, for a thing like that they didn't even want to

bother. Then one or two tasted it. And later I met some of them on the sidewalk outside the tavern. 'Tell me, chef, could you give me the recipe for that tomato pie?' So, I said, 'Well certainly.' I thought they were joking, but then they started to write it down. So we made them and they ate them. But they didn't think of it as a main course—more like a side dish. So we baked individual pieces. They had their meal and took one on the side. Sometimes we baked 3000 pieces of pizza for one meal."

Aside from pizza, there was no Italian and Jewish cuisine. The only real store in this far-flung outpost was a not very super supermarket at Lac Louise, where the trailer camp was located, and on my shopping sprees at this store I found no Italian or Kosher-style food. The workers' parochial taste in food was reflected in Imbeault's menu. They did not like lamb in any form. "There was no sense putting it through," said Imbeault. "It just went in the garbage. Besides, they wouldn't know what they were eating and say there was something wrong with the meat. I love it, and if my wife would eat it, I would regularly buy a small leg of lamb for myself." But the chef's wife and the men of Manic 5 did not like lamb, so Imbeault did without.

But he did not lose his flair for haute cuisine. "I like the wine cooking. French cuisine I love. There is nothing I love better than to make a masterpiece. I didn't charge anything extra to the company for parties and banquets, I just did them. It's my hobby. Organizing a dance or a bar, I love it. I just did it naturally because I love it.

"The trouble is some of them hadn't been around the world too much," explained the chef. "One time I overheard a fellow say, 'For God's sake, they don't even take the bones out of my meat anymore.' So I said, 'Sir, do you know what you are eating?' He said, 'No.' And I said, 'It's T-bone steak. If you take the bones out, it won't be a T-bone steak, you'll have stripped round.' And he said, 'You know, it's wonderful,' to which I answered, 'Well, you won't have it too often because we can't afford it.'"

The main cafeteria building had a private banquet room with its own entrance on the street. Hydro-Quebec's top management at Manic 5 held its VIP affairs here. For one of these, Imbeault in a sense traded his high, white chef's hat for a hardhat. He built or baked, depending on how you look at it, a cake 6 feet long and 3 feet high—an exact replica of Manic 5. "I built it as it would look when finished, so I had to have information ahead." He went to Pierre Ducharme, one of Hydro-Quebec's top engineers. "I took a good look at the model of the dam we have here at the camp. Then Pierre took me up on the dam. So, I made the whole thing, even the cableway towers, everything as exact as possible." Imbeault's multiple-arch cake was for the annual Christmas party for the executives of the contractors working on the dam and Hydro-Quebec's top brass, given by the late R. Levasseur, manager of the entire Manic 5 construction project.

A touch of old France did show up in one of Imbeault's side projects. For the man who wanted to take his lunch up on the dam, there was a kind of sandwich bar set up in the morning and afternoon for the two shifts. "We didn't make the sandwiches, because they would go bad (I wondered how many wives were aware of this). But we sliced the meat fresh every day. There was a big selection of cold meat, all packed in small packages. We had ham, cold pork, cold turkey, beef, and cheese." Workers took the makings of lunch in a bag—bread, butter, milk, cheese, jam, and sliced meat.

Was winter a problem for Chef Imbeault? "Sixty below, no problems," he said with a wave of his hand. "The trucks were always rolling. We had beautiful roads. They never stopped." A real compliment to the road maintenance crews from the man who fed them. "And when else could I make my jam?" During the dead of winter, when all but about 500 workers left the project, Imbeault stayed at Manic 5. He had frozen fruit such as strawberries brought in at harvest time and then made jam in his spare time. During 1966 there was a strike of construction workers that shut down the project and Imbeault got out his strawberries. "In three days I made up 21,000 pounds of jam."

VIII Fernand Imbeault probably never kept count of how many apple pies were involved in the construction of Manic 5. But Rock Langlois can tell you how many 100-watt light bulbs were used (between 25,000 and 30,000 per year), or that 40,000 pounds of wiper rags were used annually to clean dirty hands and wipe up oil on the project. At Manic 5 Rock Langlois directed what must have been the biggest hardware store in Quebec, a sprawling complex with an inventory of more than 40,000 different items at the height of construction, valued at more than \$6 million. Hydro-Quebec simply referred to it as the project's "Stores."

Langlois' shelves were stocked with everything from paper clips to giant grinding teeth for the project's huge rock crushers. One big quonset-type building labeled PNEUS (short for *pneumatiques*) contained \$50,000 worth of tires ranging from simple wheelbarrow tires to 27.00×33 giants, taller than a man and valued at nearly \$4000 each. Tires for the huge quarry dumps that hauled 35 tons of shot rock from the quarry to the crusher; tires for the 125 pickup trucks that forever scurried about the job like so many Dinky toys. When a vehicle needed a tire, there had to be one available. To get one from Montreal could take weeks.

These same vehicles, along with stationary machines like compressors and pumps, consumed a remarkable 800,000 gallons of fuel annually, split about evenly between gasoline and diesel oil. This was yet another of Langlois' responsibilities, along with the smallest cotter pin for any piece of equipment on the project, and a 10-foot-high spool of 1-inch-thick, 3-foot-wide conveyor belting. The mammoth spools, set up like paper toweling in a kitchen, held 1000 feet of belting, used to move crushed rock, sand, concrete, and even ice.

Keeping track of this staggering inventory and making sure that whatever was needed was on hand kept a staff of forty clerks busy at Manic 5's Stores. They had to process and handle 60 million pounds of stock every year, not including all the steel (mainly concrete reinforcing bars), lumber, cement, and gasoline. This involved filling out 25,000 receiving forms for

accounting purposes and represented about 150,000 individual items. Each had to be checked in and placed in their appropriate locations.

A machine accounting system was a necessity, since during the peak year of 1965 more than \$8.2 million worth of new stock came into Manic 5's Stores, and the operation supplied \$8.4 million worth to the project. This was done via Hydro-Quebec's computer at its Manic-Outardes headquarters in Baie Comeau. Every one of the 40,000 items had its own code number and at any given time Stores could determine how many of a particular item were on hand.

Pointing up the fact that Manic's big hardware store was only a temporary operation was a category of inventory labeled, oddly enough, "permanent inventory." This applied to any item that was an integral part of the dam or powerhouse. For example, a certain valve or piece of pipe that Stores had on hand because the engineering department had called for it in the project plans and specifications was permanent inventory. It remained in the warehouse until it was installed in the dam. It was then eliminated from the inventory and not replaced like a windshield wiper or a spark-plug.

As an indication of the importance and the complexity of the project's aggregate and concrete operations, Langlois had one entire warehouse devoted to parts for the crushers, conveyors, screens, mixers, and thousands of other moving parts, each in its own way critical to turning out the millions of cubic yards of concrete for Manic 5. The unavailability of one small part is all it would take to disrupt the high-speed mass production of concrete.

While inspecting a huge part for a rock crusher, I asked Rock Langlois if he could help me had I broken a window in the room at my camp. "Not only do I have the glass, but I have the mastic and the glazier's points," he boasted. I restrained myself from asking how many glazier's points he had on hand, but I suspect he could have told me.

Langlois seemed to have everything imaginable in stock, but I was determined to trip him up. "Where would a girl get a brassiere or a man a suit of clothes?" I asked. Smiling, Langlois pointed down the hill toward the camp and said, "Where else—at the restaurant." I should have known—the general store sold everything.

Back in the office of CFQ's director Rosset I posed the same question. He admitted that until about 1966, the ladies had either to buy such things as bras through mail-order houses or go to Baie Comeau where the Hudson's Bay Company had a large modern department store. "In 1966 we opened a small shop up at Lac Louise, which sold most of the ladies' staple items, plus children's clothing. But here at the restaurant we carry a stock of about 100 to 130 readymade men's suits. If someone wants a made-to-order suit, we can order it up from Montreal. We carry McGregor sportswear," he

boasted. (Most of the people on the project, even in offices at the top level, wore sports clothes—sport shirts and slacks for the men, ready-to-wear separates and so forth for the girls.) “We’re the only ones who wear suits here,” said Rosset. “We have to do our own advertising.”

Rosset explained what may be a side effect of living in the bush. “The people here are really proud. Why, up at Lac Louise, you’ll see a little boy seven or eight years old so well dressed you won’t see any better in Montreal. Nothing but the best. It seems to be some kind of compensation for being way up here. You don’t even realize it yourself, but if I’d be in Montreal, I might buy three or four suits a year. Well, all of a sudden I say, ‘Hell, I can’t afford that suit.’ But up here you don’t even think about it. Spring is coming, you need a couple of suits, you don’t even think about it; you go out and you buy a couple of suits. I think it’s psychological. You want to compensate for some of the things you haven’t got. It’s obvious, but I don’t think anybody notices it.”

Although CFQ’s general store was by no means the proverbial company store, workers could buy on credit. “Conditions are pretty much the same as on the outside, where if a man was known to be honest and his credit rating was good, there’s no problem,” said Rosset. “He can buy a TV or stereo just as if he were in Baie Comeau, Montreal, or New York.” Better yet, the installment purchases involved absolutely no interest charges. “Right off the bat, the client saves between 6 and 9 per cent,” said Rosset. “A lot of people on the project don’t realize how well off they are in this respect.”

Predictably, most workers did feel exploited since there was only one



store on the project. "They can charge whatever they want; where else can we go?" was a typical remark. On the other hand, if the concessionaire were to charge outlandish prices, Hydro-Quebec could easily have terminated the contract and brought in another company. Rosset explained some of the disadvantages of what might appear to be an ideal selling situation—a captive clientele and no competition.

"Your responsibility is greater. Suppose I have ordered 100 parkas for winter which is upon us. A strike somewhere else delays the shipment. The customer, as well as Hydro-Quebec, complains: 'Where are the parkas? It's cold outside.' The customer cannot walk up the street to another store. He needs the parka. We have to get on the phone and begin shopping around in Montreal. We sometimes flew in shipments when it was something critical like parkas or thermal underwear. Men who work outside can't do without these things. There are many problems, but that kind of a situation has a much more telling effect on us than on an ordinary retail store in a city."

In fact, Rosset's job at Manic 5 was considerably more involved than a retail storekeeper's. CFQ also was charged with operating the tavern, a kind of beer hall for the workers. Hydro-Quebec had strict regulations for the use of alcoholic beverages. The tavern served only beer. Beer and hard liquor were not allowed in the living quarters, except in the trailers at Lac Louise and the senior staff quarters.

This pretty well confined the drinkers to the tavern and the Club des Contremaîtres, a private club for supervisory people of the level of foremen and up. The hours of these establishments also were designed to limit drinking. The tavern was open from eight to ten in the morning (for the night shift) and from seven to ten at night. The foremen's club was open until eleven at night. The theory seemed to be that while such limited hours might not keep a man from getting drunk, he would at least have recovered by the time he had to go to work.

Drinking and occasional brawling can tend to be a problem on remote construction sites like Manic 5, despite all the efforts of agencies like Hydro-Quebec to provide other things to do. Among those other things was an almost endless list of activities: movies; special variety shows; sometimes imported talent, such as popular singing groups; pool and billiards; bowling; softball; and track and field meets.

Manic 5's Service des Loisirs (recreation section) also provided facilities for badminton, basketball, volleyball, tennis, table tennis, archery, darts, curling, fencing, croquet, and both target and trap shooting.

For the more sedentary, there were the *jeux tranquilles*—pinochle, checkers, chess, as well as courses in cooking, sewing, art, child care, beauty culture, and interior decorating.

And, of course, there was the favorite sport of all Canada—ice hockey.

To handle this, the big arena, a cavernous building used as a gymnasium in summer, was made into a hockey rink by simply turning off the heat in November and flooding the concrete floor. Once the ice formed, Manic 5 was ready for hockey and curling, the stone-sliding game with the brooms, which strikes the American observer as a kind of crazy form of shuffleboard. Temperatures remained so low in winter that the heat could be turned on in the arena for hockey games and curling matches without affecting the ice.

For the non-competitors there was always skating on frozen Lac Louise, which of course in the summer was available for boating. Most summers saw about fifty small boats on the lake and several sailboat regattas. For the very brave, mostly children, there was swimming and water-skiing in the frigid (about 50 degrees) water. In addition to all this organized recreation, there was the surrounding countryside, an absolute paradise for fishermen and hunters. Fish stories abounded at Manic 5—weights and lengths of trout and bass I found hard to believe; game fish with strange Indian names that “literally jumped into your boat.”

The hunters, on the other hand, were a more pretentious lot, driving through camp with moose antlers mounted atop their cars and pickup trucks. From late September through mid-October a brewery sponsored the Grand Concours de Panache Molson, a moose-antler contest (“Panache” is antler, “Molson” the beer). Prizes up to \$300 were awarded for the best set of antlers judged on both size and quality.

And the recreation program did not forget those hardy souls who



stayed the winter at Manic 5. Hydro-Quebec built a ski tow not far from Lac Louise. Since the project ran around-the-clock, it was assumed correctly that skiing would have to go around-the-clock also. The ski tow was lighted at night so the man who had wrestled a rock drill all day could mount his boards at night.

Recreation director René Larouche admitted that even with such a variety of recreation available, one of his problems was preventing fights during the sporting events. "The men come down off the dam, tired after a day's work, and they try to play ball, for example. Sometimes they are too tired, and fights develop." But also, despite Manic 5's recreation program (which was vastly better than those in most communities) a lot of the workers ended up behind a bottle of beer. There is a kind of restless boredom that seems to overcome people isolated in the bush country, and the biggest law enforcement problem, according to the police at Manic 5 (a small unarmed force hired by Hydro-Quebec), was drunkenness and disorderliness. One reason the police did not carry guns, a young officer explained, was that it was considered dangerous to wade into a brawling group of workers with a sidearm. "They might take it away and use it on you or their friends," he said.

Otherwise, the Manicouagan police had a rather quiet job. They had to patrol the highway down to Mile 70, which involved handling a startling number of traffic accidents (most involving private automobiles). They attempted to keep the men out of the girls' camp buildings and naturally had



their share of domestic quarrels to cope with, but no one had ever even tried to rob the bank.

This may have been partly due to the location of the latter—directly across the camp's gravel main street from the Poste de Police. The police chief and the bank manager both figured there had never been a bank holdup because of the difficulty in making a getaway. The bank was at one end of a weathered sheet-metal building also shared by the post office. In fact, if you did not check carefully for the small gold-lettered sign heralding BANQUE CANADIENNE NATIONALE, you often ended up in the post office. The clue was a 10×10-foot concrete block addition on the rear of the bank—its vault.

Inside, the bank had wasted none of its depositors' money on frills. Highly varnished plywood formed the counter and tellers' cages. The floor was covered with asphalt tiles. Two youthful tellers in sport shirts manned the cages, while the usual group of female typists and clerks worked at desks behind the counter, all dressed casually, in the Manic 5 manner.

In general the bank at Manic 5 was like any other. It did handle an impressive payroll, the amount of which the young manager would not reveal (presumably to avoid any publicity which might encourage someone to attempt the first robbery). One unusual aspect of this bank to which the manager readily admitted: "Occasionally we run out of money." This happened a few times when there was an exceptionally heavy demand for money, such as when too many Manicouaganites decided to take weekend trips.

Although the regular bank may have run out of cash now and then, there was another bank at Manic 5 that never ran dry—the blood bank. The dam builders of Quebec were remarkable. They set records at Manic 5 with their blood donations, year after year winning provincial awards for the most pints from an industrial group. The time I donated, I was one of 1402 donors in a two-day visit by the Red Cross. This amazing turnout came from a total population—men, women, and children—of less than 3500.

There were many theories about why the workers of Manic 5 were so generous with their blood. Some said it was typical of construction men—men who often worked in constant danger, who have seen others hurt and killed. Men who see blood spilled in their business are quick to donate to a blood bank. Tomorrow, it might be they who needed some. Other less romantic theories were that the men donated in order to get time off from work or that their foreman simply said, "Allez . . . to the blood bank," and since most of the gang was on the truck, the laggards were embarrassed into going along.

Many a community back in civilization should have the so-called temporary medical facilities that Hydro-Quebec provided for its workers. One of

the more obvious grayish metal buildings at Manic 5, although it was out of the mainstream of the camp, was the hospital. It stood out because of its tall flagpole flying the red cross. The hospital had twenty-three beds with three operating rooms, one for obstetrics, another for emergency, and the third for minor surgery. Normal staff was about seventeen nurses and two doctors.

There were modern private rooms and laboratory facilities for blood tests and pregnancy tests. The nursery had a capacity of five babies and there was a pleasant children's ward. A typical year was 1965 with about eight hundred patients and seventy-one births. The hospital tried to handle only minor surgery, but in emergencies sometimes handled more involved cases. One was the case of a little boy attacked by a wolf while out camping with his parents. Doctors were unable to save him, but other accidents demonstrated the importance of good local medical facilities.

One worker fell about 90 feet off the intake structure and was impaled on a big reinforcing bar. As one Hydro-Quebec executive later explained it: "That chap should have been dead. But he lived; he went back to work. It was because he was on our job. He would have been dead in Montreal. We had special doctors and nurses, lots of blood on hand. We phoned to Micoua [about halfway down the road to Baie Comeau]; we had twenty pints of blood to keep him going down to the hospital at Baie Comeau. He could not have got that in Montreal, never in his life. For one thing, there never would have been an expert there immediately to cut off that steel bar."

Although there were accidents on the project, the hospital was kept busiest by automobile accidents on the road to Baie Comeau, mostly all to workers driving their own cars. Manic 5's two ambulances made most of their calls down along the road. With an annoyed look, safety director Jacques Morand said: "The Montreal papers once made a big thing out of how seventy-five men had died on the Manic-Outardes development. But they failed to mention that sixty-five of them died driving their own cars on the road!" Actually, only twelve lives were lost during the decade that Manic 5 was under construction.

IX During the summer of 1962 concrete crews plugged the meticulously cleaned-out deep gorge with a massive block of concrete. But not before the geologists had gone over the slot with a fine-tooth comb. They even used television and still cameras inserted into deep drill holes to investigate the surrounding rock that would underlie the dam. These experts in the science of rock mechanics wanted to know all they could about the structure, mineral composition, mechanical properties, and the general conditions, such as faulting and seams, of the rock that would have to support the string of concrete arches estimated to weigh about 6 million tons.

Since no so-called solid rock or bedrock is completely homogeneous, the geologists knew they would have to perform some remedial measures on the foundation rock. The rock of the Manicouagan gorge had its share of faults, mainly uplift faults caused by pressures created when the 2-mile-thick icecap receded at the end of the Pleistocene epoch. There were also the usual fissures and seams caused by stresses in the earth's crust.

With all the preliminary exploration completed and recorded, actual excavation for the main arch and its buttresses got under way. Such work appeared to be a simple matter of blasting out a scalloped series of wide trenches in the rock, mainly to remove inferior rock damaged by chemical decomposition and frost, described loosely as "weathered rock." But mining out this weathered rock to form the dam's foundations was one of the most critical aspects of the job. One of Surveyer, Nenniger & Chênevert's geologists with the unlikely name of Rock Poulin, explained it this way: "Having made a geologic map of the surface rock exposed by removing the overburden [dirt and loose rock covering the bedrock], you then excavate. You excavate to a theoretical depth. Then you examine the rock bottom once the shot rock is removed and the excavation cleaned and prepared for concreting. Then you map again. We call it surface mapping. It's just like taking a photograph. We have survey points, control points, and topographic data, and everything is blended in to give us a reproduction of the ground, a kind of geologic photograph."

At this point the geologist is concerned not only with the dam's stability, that it be founded on sound rock, but also with the permeability of the foundation. A so-called solid rock foundation might be sound enough to support the structure, but fractures and seams in the rock still might allow seepage, especially under the very high pressures that develop behind a dam as high as Manic 5 (its operating head of 505 feet of water depth meant pressures up to 220 pounds per square inch).

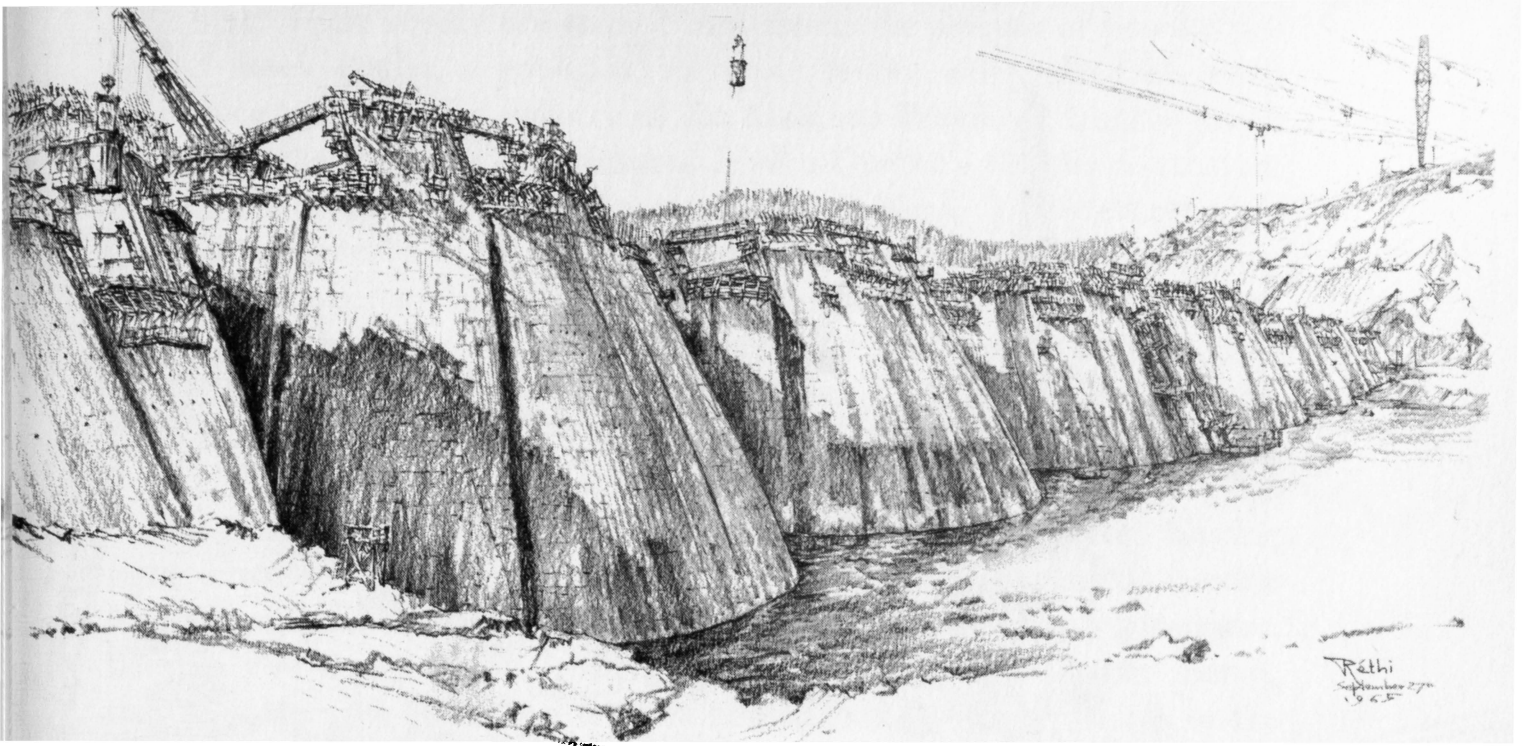
This type of uplift pressure is particularly worrisome on a gravity dam, in that sufficient pressure on even a huge block of concrete can lift it, thus allowing it to move. But at Manic 5, with relatively small areas of contact with the rock, this more common type of uplift was not a great worry. But another more unusual type of uplift problem was taken into account.

If uplift pressures build up high enough in the rock under an arch dam, the tremendous forces can literally break the rock downstream from the arch. The action is similar to, but more violent than, the sand boils which sometime develop behind river levees during a flood. "This is one of the things we were concerned about at Manic 5," said Poulin. "If this type of seepage under high pressure should occur, and the rock should fail downstream of the dam, then the stability of the arch is threatened. This is what we're trying to prevent," he said. This was the uplift that designers were most interested in, as opposed to the more common type of direct uplift pressure on the base of the structure. "Actually," Poulin continued, "we did have to worry about conventional uplift pressures on the buttresses of the main arch, since they measure more than 100 feet across at their bases. And we also had the less common type of uplift that breaks the rock downstream of the dam."

The French have a word for it—*claquer*, which translates roughly as "snap" or "clap." They also apply the term to grouting. If grout, a mixture of cement and water, is injected into fractured rock under very high pressure, it will break the rock at the surface in an almost explosive manner, hence the word *claquer*.

At any rate, the geologists inspected every excavation, carefully mapping every characteristic of the exposed rock. Their purpose was twofold: to decide if the excavation was sufficiently deep and to determine what type of treatment the foundation rock would require to prevent any possible seepage even in formations far below the point where the rock and dam make contact.

At this point in his explanation, Poulin got on what seems to be his (and probably many other geologists') pet peeve. "Sometimes we sacrifice quality for speed," he said. "If you start blasting with too much powder [a misnomer often used to mean dynamite], then you're going to break the



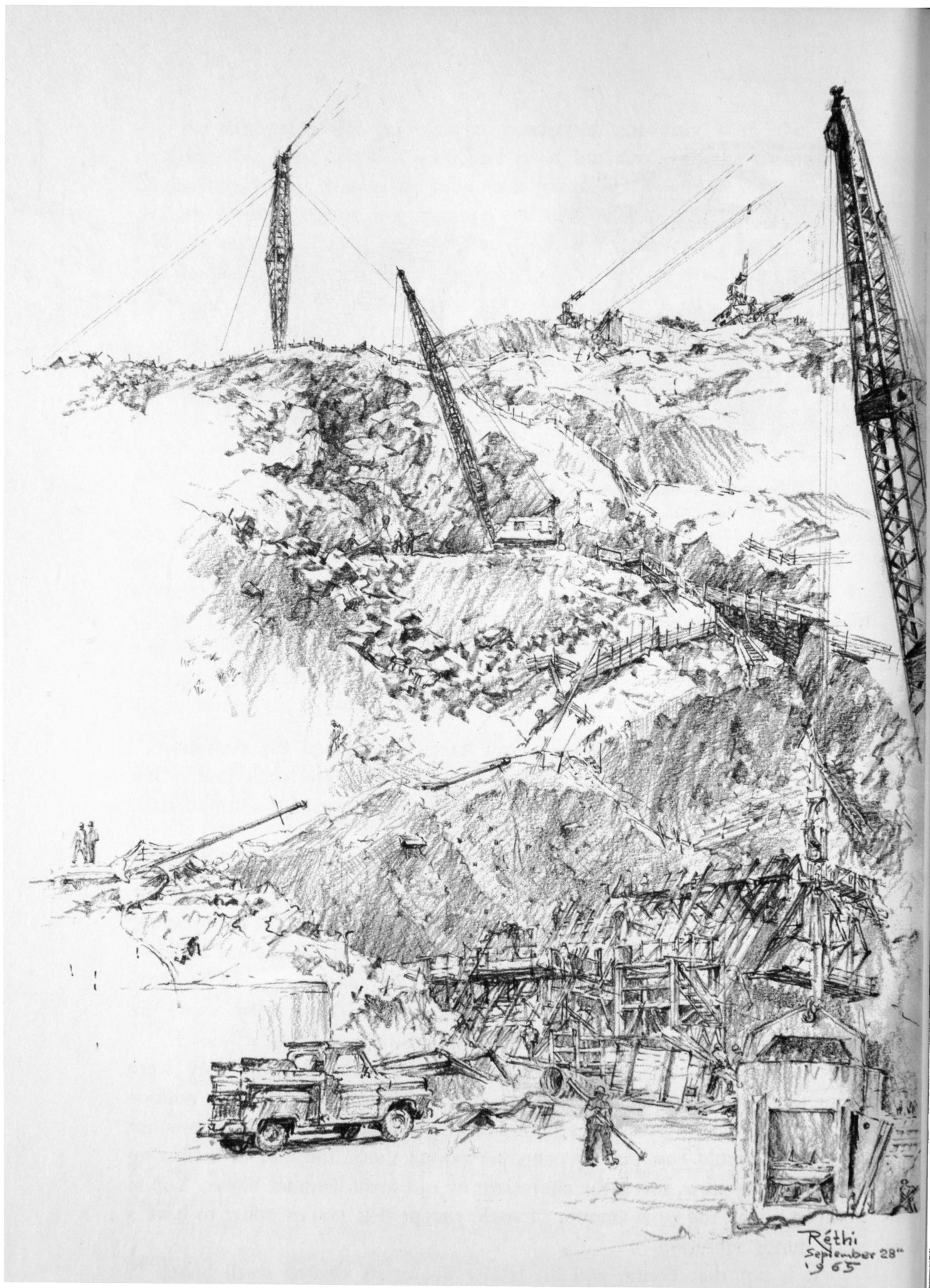
Water laps at dome-like upstream faces of an ever-lengthening row of arches as concreters work in as many as twenty-five locations in a single day.

bottom. If you break the bottom, you haven't improved the conditions." In other words, if the charges used to excavate the initial rock foundation are too big, they can damage the rock designed to be used for a foundation. Then the rock must be re-excavated.

"The blasting men tell me they're only using $\frac{3}{4}$ of a pound of dynamite per cubic yard of rock. Now me," said Poulin, "I don't give a damn for that. I don't care if they use $5\frac{3}{4}$ pounds per cubic yard. What is important for me is the stability of the dam. What is important is the amount of powder per period." (A period is the time between detonations created by blasting delays such as Janin's hard-rock tunnelers used. These delays cause the dynamite to detonate at closely spaced intervals instead of all at once.)

"In a blast that they were doing here," explained Poulin, "they were using 140 pounds of dynamite for one bench. Now how is this 140 pounds used? If you blast 1 pound at a time, you're going to break the same amount of rock. It would cost you 15 cents per pound more, the cost of a blasting cap. In theory now, this is the equivalent of 140 small hammer blows. You're going to break the same amount of rock, except that you're going to have a very minor vibration."

It is not that Poulin and his fellow geologists desired small blasts. "I don't care if you use 1000 pounds of powder; I don't care about the size of



Crane high on slope works on excavation for the dam's most westerly arch, while second rig in foreground hefts concrete bucket for buttress. This portion of dam is beyond the reach of the aerial cableways.

your blast. There is only one thing I care about: the amount of powder per delay.” Rock Poulin, a youngish, roly-poly fellow who gained his early experience in the mining country of the Maritime Provinces, laughed when he told of the time that SNC insisted Hydro-Quebec’s blasters re-excavate for several of the arches on the west end of Manic 5 “to everybody’s horrified surprise.” But the blasting in the initial excavation was too heavy and they had to be taken deeper. The foundation rock had been broken.

This, incidentally, illustrates the interesting relationship between consulting engineers and their clients, in this case, SNC and Hydro-Quebec. SNC could not tell Hydro-Quebec’s blasters how to do the excavation. Said Poulin: “These guys could do whatever they wanted, but I approve the results, eh? I accept the bottom of the foundation. So they can keep blasting right down to the center of the earth as far as I’m concerned, because I’m not going to accept it, right? So, it’s sort of a gentlemen’s agreement. Because you accept the bottom, well, just to shut your bloody mouth, they’re going to do what you tell them to do. That way my back is to the wall. I can’t yap or complain. If I did, they would say, ‘Well, what do you want? We did what you said.’ This is a cat-and-mouse business, eh?”

But despite Rock Poulin’s laments about overenthusiastic blasters, Hydro-Quebec’s crews did some extremely precise blasting for the foundations, using a then new technique called “cushion blasting.” In essence, this technique was similar to the tunnelers’ tightly controlled blasting method. Blasters working on the surface, such as in a quarry, generally are less concerned with overbreak and damage to the surrounding rock. Their primary objective is to create a large excavation in the rock, shoot as much rock as possible each time. The amount of dynamite used is a matter of economics, aimed at a good powder-to-muck ratio—the pounds of explosive used per cubic yard of muck or shot rock. But when the engineers and geologists get sticky about the condition of the surrounding rock after the blasting operation, the powder men usually blast in steps. First they shoot the main area to be excavated, then come back and trim out the edges with small, carefully controlled shots. At Manic 5 the Hydro-Quebec powder men began excavation for the arches and buttresses in just this way. After initial shots showed that the seamy, but nevertheless sound rock was not going to be too troublesome, Hydro-Quebec engineers decided to try the new system of cushion blasting recommended by their powder supplier, Canadian Industries Limited. Cushion blasting is a kind of refinement of an older, yet still relatively new, method of controlled blasting called “presplitting.”

Presplitting involves drilling blast holes along the perimeter of the area to be excavated and shooting these holes with light charges ahead of the main blast. This cracks the rock along this perimeter line prior to the main

shot, thus preventing most of the shock of the main blast from being transmitted to the surrounding rock. Cushion blasting accomplishes the same thing in one blast instead of two. The holes are drilled in the same way and blasting delays are used to cause the lightly charged perimeter holes to fire slightly earlier than the main charge. Actually, most of these main charges on the surface were fired with the same basic V-cut described in the construction of the diversion tunnels. The charges in the center detonate first, at what powder men call "zero delay," with the other delays radiating from the center V outward toward the perimeter. The point of the cushion blasting system was that the perimeter holes also fired at zero delay, simultaneously with those in the V-cut. Hence, the perimeter holes presplit the so-called break line just before the full force of the main blast reached it.

Using this technique, Manic 5's powder men carved out the intricate foundations for the dam's many arches and buttresses with better than split-second precision—millisecond precision best describes it.

While blasters and geologists worried over preparing the rock foundations for the dam down in the gorge, other drillers and blasting men were high up on the east mountain setting off huge shots. These men were not particularly worried about the surrounding rock. Their job was to turn the solid rock, just over the summit from the damsite, into small enough pieces for a giant rock crusher to begin making it into concrete aggregate.

This was Manic 5's quarry which would eventually have to provide nearly 10,000 tons of shot rock a day to keep up with dam concreting, and the quarry's dynamite blasts were anything but cushioned. In a way the quarrymen were sort of unsung heroes of the project. Drill holes, charge them with dynamite, detonate it, load the broken rock into trucks, and then repeat the cycle—that was their job, a routine removed from the project.

But every day at 6:10 P.M. the powder men at the quarry reminded the camp—and anyone else within a radius of 10 miles—that they were on the job. At 6:10, with the project relatively quiet because it was dinner time, a deep-throated steam whistle would honk twelve times, sending puffs of steam up on the west bank just downstream from the dam. Soon after the last honk had echoed across the gorge, the entire valley rocked with the force of a heavy explosion. Windows rattled and the ground underfoot shook even far on the other side of the valley. Immediately the whistle would give forth with a long serenade; with a slight tremolo in its voice, it announced the all-clear. A tall plume of steam floated away from the whistle and the daily blast at the quarry was over.

A dull job, despite all its noise, but still of major importance. Remembering the dry recipe for a cubic yard of concrete—394 pounds of cement, 1225 pounds of sand, and 2290 pounds of crushed rock—the immensity of the quarrymen's job at Manic 5 becomes apparent. They had to

provide more than a ton of crushed rock for each of the 3 million cubic yards of concrete required. The quarry actually had to produce even more than that, because of wasted rock in the form of dust and fines lost in the crushing and screening process.

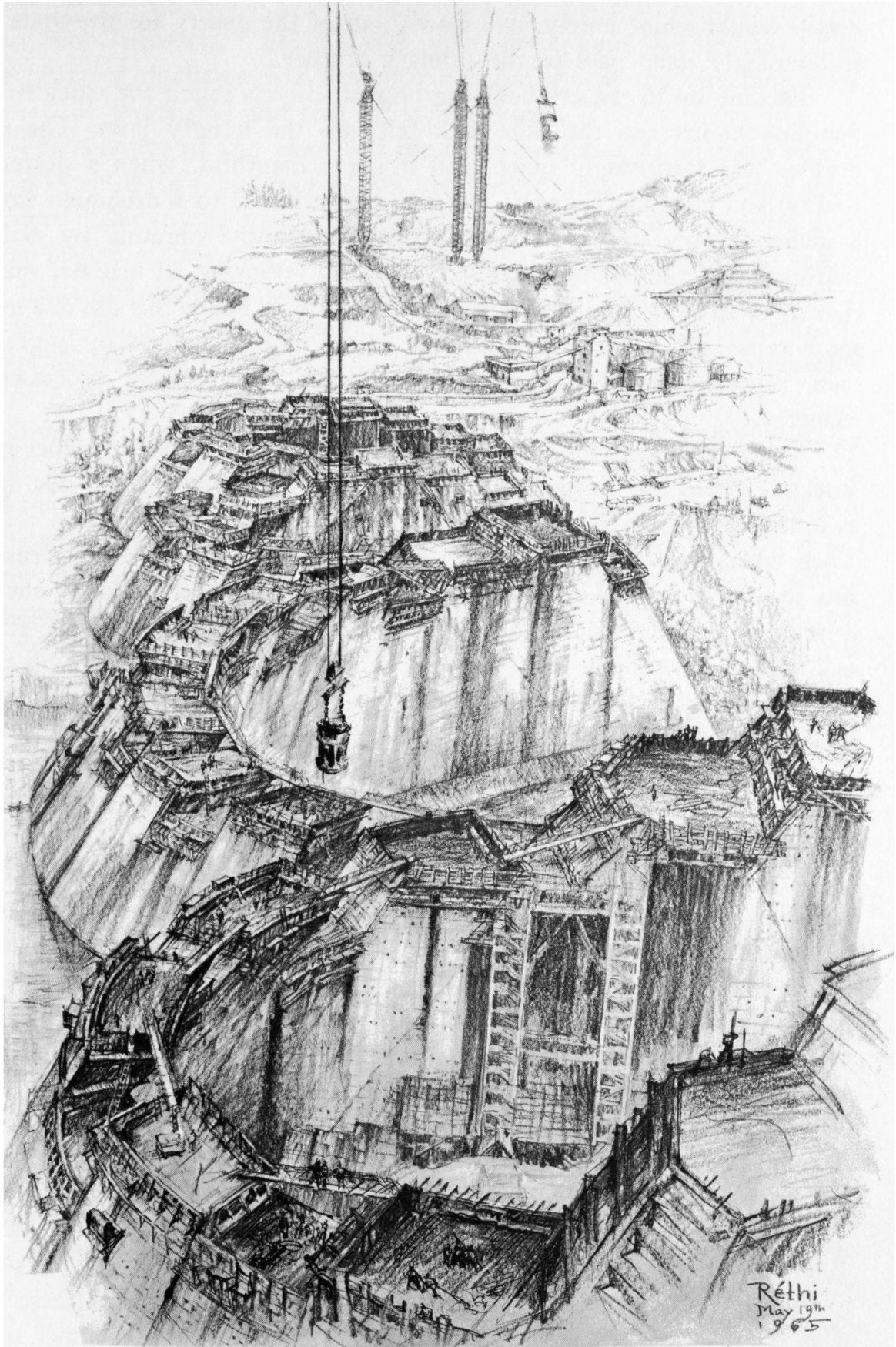
A far cry from cushion blasting, the quarrymen drilled 6-inch-diameter holes for their dynamite. In a quarry the object is to break as much rock as possible with the least amount of drilling and dynamite. Of course, the rock has to break into pieces small enough to be handled by the loading equipment and the primary rock crusher. In fact, Manic 5's quarry eventually switched to 2½-inch-diameter holes, and more of them, as an efficiency measure. Using the big blast holes, there was no problem with loading—a big electric-powered shovel could handle huge chunks of rock—but the primary crusher could only handle rock up to 48 inches across. There was hardly a day that passed without at least an hour or two of lost time at the big crusher, while workmen hauled an oversized chunk of rock out of the crusher's massive forged steel jaws. Primary crushers usually have two huge corrugated jaws. Like a great flat open mouth, the jaws vibrate and as the pieces of rock approach the narrowing throat of the crusher they are crushed into smaller and smaller pieces. If a piece of rock is so big that it cannot enter the widest point of the crusher's jaws, it must be removed.

X The man who decided that smaller drills in Manic 5's quarry would increase aggregate production was Cliff Barrington, one of the few top management men on the project who was not a French Canadian. Barrington, a big semibald man with more than thirty years of heavy construction experience on projects all over the world, actually had a Scottish brogue—a particularly humorous accent when he spoke French.

Barrington was in charge of the vast aggregate operation and eventually took over responsibility for maintenance and operation of all the equipment on the project. This was a fairly logical step since providing sand and aggregate for the voracious concrete mixing plant probably involved more major equipment than any other aspect of the project. Considering that Rock Langlois had one whole warehouse full of spare parts just to keep Barrington's crushers, conveyors, and screening plants operating, it was not surprising that Hydro-Quebec made Barrington responsible for all the project's equipment. It also was not surprising to find Cliff Barrington and his administrative assistant Luc Desrochers working eighteen-hour days. There was always a problem somewhere on the job, and nine times out of ten it involved equipment. The project ran around-the-clock, and since mechanical equipment gets tired, Barrington often ran around-the-clock too.

His manufacturing operation, producing 4000 tons of sand and 8000 tons of crushed rock each day, was enough of a challenge. Barrington had two manufacturing plants, the sand-classification plant at G-13 about 7 miles from the dam and the great crushing and screening plant that clung to the mountainside on the east side of the river just downstream of the dam's axis.

The process of turning nature's raw materials into ingredients for concrete began as soon as the big 35-ton dump trucks took on shot rock at the quarry. During the years of peak concrete production, a big 5-cubic-yard electric-powered shovel filled the trucks at the quarry. Despite their size, the massive off-the-road dump trucks seemed to groan as the bucketloads of broken rock thundered into their heavy steel bodies. Once loaded, these big



View along dam's axis emphasizes complicated formwork required for multiple-arch structure. Although some monoliths in arches appear to remain constant, the decreasing thickness of the dam as it rises causes continuous adjustment of the forms.

diesels would whine loudly, pull slowly out of the quarry for the short but frighteningly steep haul to the primary crusher.

Backing up to the crusher's big hopper, drivers raised the truck's rear-dumping bodies and the shot rock fell into the hungry jaws. The rock crusher was surprisingly quiet until it got a mouthful, when a deafening roaring and cracking began as the rock was reduced to a maximum size of 8 inches. Heavy steel-mesh screens, kept constantly vibrating by electric motors, sifted the primary crusher's product, removing all material smaller than $\frac{3}{8}$ of an inch. A conveyor belt took all material below this size to a mammoth reject pile. This waste material, called dust or tailings by aggregate men, represented about 16 per cent of the rock volume processed at Manic 5.

Other conveyors took the mixture of larger-sized rock to another giant stockpile called the "surge pile." Barrington would build this big pile up to as much as 175,000 tons of rock at the end of each construction season. Then when concreting began the following spring, the secondary crushing and screening plant would draw from the bottom of this pile as the big crusher continued to add to the top of the pile. Basically, the surge pile served as a reserve to keep the concrete plant in continuous operation should there be a shovel breakdown in the quarry or a hang-up of some kind at the primary crusher.

All large aggregate operations try to make use of gravity as much as possible. This is done by using what are called "reclaim tunnels." Before a stockpile of rock or sand is created, a concrete or steel tunnel is built in a trench; the material is then piled on top of the tunnel. Automatic or manually controlled gates, similar to those in a railroad hopper car, are installed in the tunnel roof and a conveyor belt leads out of the tunnel. This way material can be removed from the pile without using a shovel or other loading device. The gates are merely opened and the material falls onto the moving belt. Generally the tunnel is made long enough to handle several stockpiles. In a semiautomatic system such as Manic 5's, the operator merely pushed a button to close the gate under one pile, opened another gate the same way, and thus delivered whatever size of aggregate was needed to the batch plant.

Barrington's coarse aggregate involved four piles; the finest, $\frac{3}{8}$ -inch to $\frac{3}{4}$ -inch; then $\frac{3}{4}$ -inch to $1\frac{1}{2}$ -inch; then $1\frac{1}{2}$ -inch to 3-inch; and last, 3-inch to 6-inch. The secondary crushing and screening plant created these four piles by drawing from the surge pile via another reclaim tunnel under it. The first stage of the secondary plant was a screening operation that separated all the rock under 6 inches into the appropriate size ranges and separate conveyor systems delivered the material to its respective pile. All the pieces of rock that did not pass the 6-inch screen were sent to crushers,

called "cone crushers," which broke these pieces into smaller sizes. The cone crushers' discharge was then lifted to the top of the screening plant again to be segregated and sent to the stockpiles.

The concrete mixing plant was the final destination of all these various sizes of crushed rock, but the rock got one final treatment before riding more conveyor belts to the top of the big batch plant. Hydro-Quebec's consulting engineers, Surveyer, Nenniger & Chênevert, specified that all aggregate had to be sparkling clean before going into the concrete, so the final step was a thorough washing and drying. (Dirty aggregate can considerably reduce the strength of concrete by preventing the bonding action between the rock and sand aggregate and the water-cement paste.)

Manic 5's aggregate, therefore, passed through an elaborate washing station on its way to the batch plant. Water jets, with high-pressure air mixed in, washed all dust from the stone and finally air jets dried the rock as it moved to the bins atop the batch plant. These bins held enough of the various aggregate including two sizes of sand to make 500 cubic yards of concrete. But considering that the plant's four big mixers could turn out 400 cubic yards of concrete each hour, the aggregate men could not fall far behind. In fact, if the dam builders were going to put 3 million cubic yards of concrete in place by 1968, nobody could afford to fall behind.

Barrington's other manufacturing operation was out at G-13, the big sand deposit. "Manufacturing" might not be the right word since his men were not really making sand from something else. They were, in fact, making sand from sand—turning bad sand into good sand by a process called "classification."

If the engineers were particular about the quality of the coarse aggregate, they were downright fussy about the sand to be used in Manic 5's high-strength concrete. They were so concerned that they built a \$1-million sand-classification plant at G-13, designed to turn out 4000 tons of sand of precisely the quality specified by the concrete experts.

Actually, classification began right in the pits as the sand was dug from the ground. Big rubber-tired loaders scooped the sand from the various formations and giant end-dumps, borrowed from the quarry usually at night, hauled it to the classification plant. Just three of these huge trucks were able to haul enough raw sand in one night to supply the sand plant for two ten-hour shifts. The trucks dumped their loads in one of four stockpiles at the plant, ranging from coarse to very fine, according to the general size range in the formation being mined at the pits.

Since the sand-classification plant was going to sort the sand into about a dozen different sizes, then reportion it, mixing various sizes so that the end product was exactly proportioned to the design specifications of the concrete, the raw sand entering the plant had a direct bearing on the amount

of waste. For example, of the 165 tons of sand the plant turned out each hour, only so much coarse sand was needed; if the raw sand entering the plant had a high percentage of coarse particles, the plant would automatically send it to the waste pile.

In an attempt to hold down the amount of waste, engineers insisted on a preliminary sorting process before the sand got to the plant. The four stockpiles were atop a reclaim tunnel with a gate under each pile. To provide a fairly well-blended mixture at the start, a man in the reclaim tunnel worked the gates to blend the sand from the various piles as it fell on the conveyor belt leading to the top of the sand plant. To produce its average 2000 tons of sand per shift, the plant consumed about 2700 tons of raw sand. Sometimes, even with the preliminary blending, the plant rejected as much as 45 per cent of the sand fed into it.

The actual classification process began as soon as the sand left the reclaim tunnel. Since every sand deposit included some gravel and cobbles, the plant first had to get rid of them. A large vibrating screen caught all of these more than 3 inches in diameter and another conveyor carried them to a reject pile near the river bank. Next, a second screening operation took all the gravel from 3 inches to $\frac{3}{8}$ inch and separated it from the sand. This is called "scalping." Instead of rejecting this finer gravel, the plant sent it to a crusher that literally made it into sand and sent it directly back to the classification process. A final screen scalped off anything more than $\frac{1}{8}$ inch in diameter just prior to the delicate part of the operation.

At this point the highly automated plant actually used a natural phenomenon to sort and reportion the sand. In effect, the plant performed, under highly controlled conditions, the same action that a running stream does with the sand and silt that it carries along. The process began high in the top of the big building, which looked something like an old-fashioned coal tippie. Once past the screens, the remaining sand was mixed with water to make a kind of gritty soup. This soupy mixture then went at a controlled pressure into a long tank. Here is where the engineers took a leaf from nature's book.

Just as they would in a running stream, the heaviest or largest particles fell to the bottom at the upstream end of the tank. The very fine grains dropped to the bottom at the far end of the tank as the velocity of the mixture decreased. The water, which had deposited all but the very finest sand particles, spilled over a lip at the end of the tank and was recirculated.

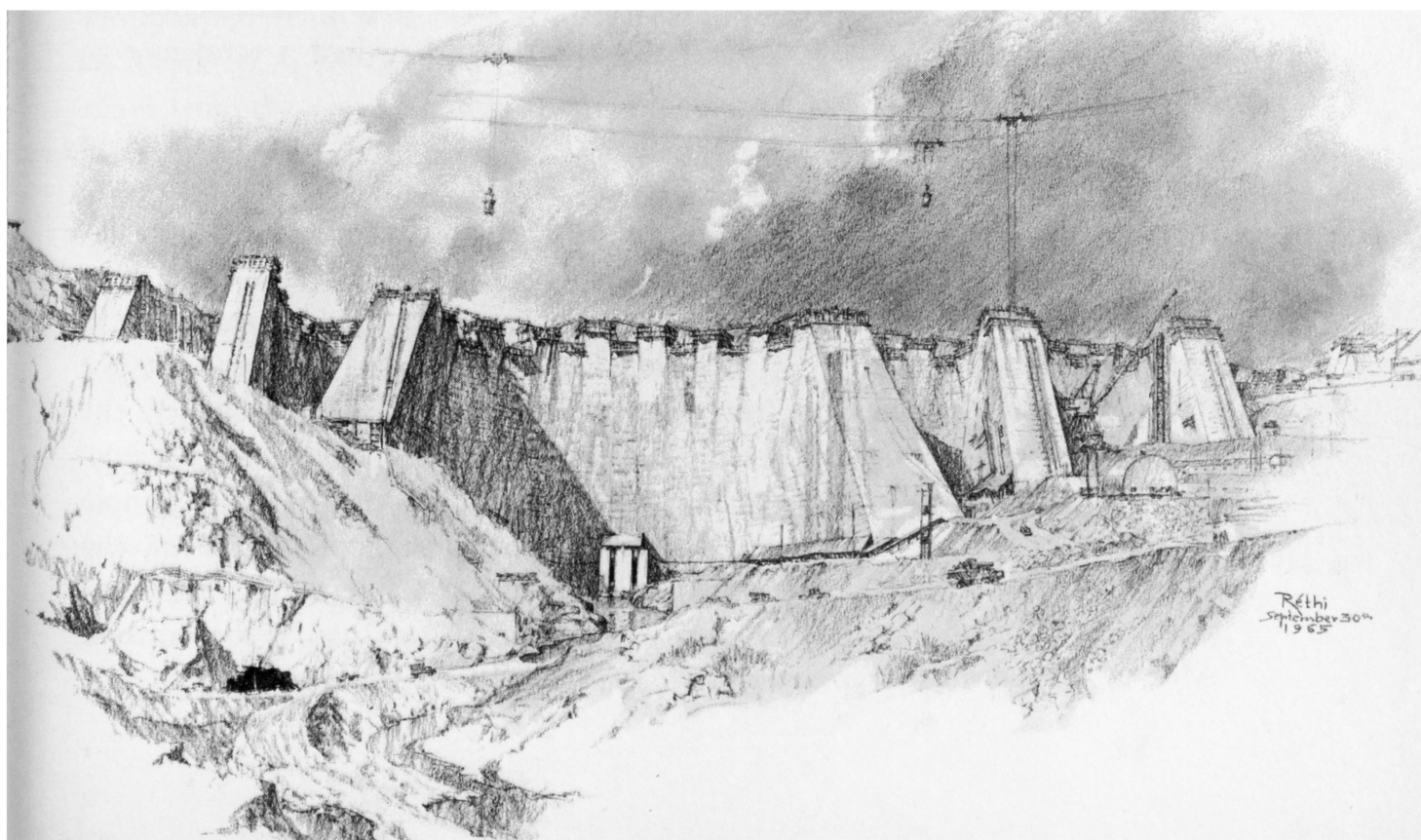
"The sand is cut in twelve proportions," explained Luc Desrochers, Barrington's assistant. "This is done blindly. We don't see anything, as it occurs underwater, but if you drained the tank, inside you would find twelve little piles of sand. Electric valves under these little piles open up for so many seconds for each type of sand. If one of the piles gets too big,

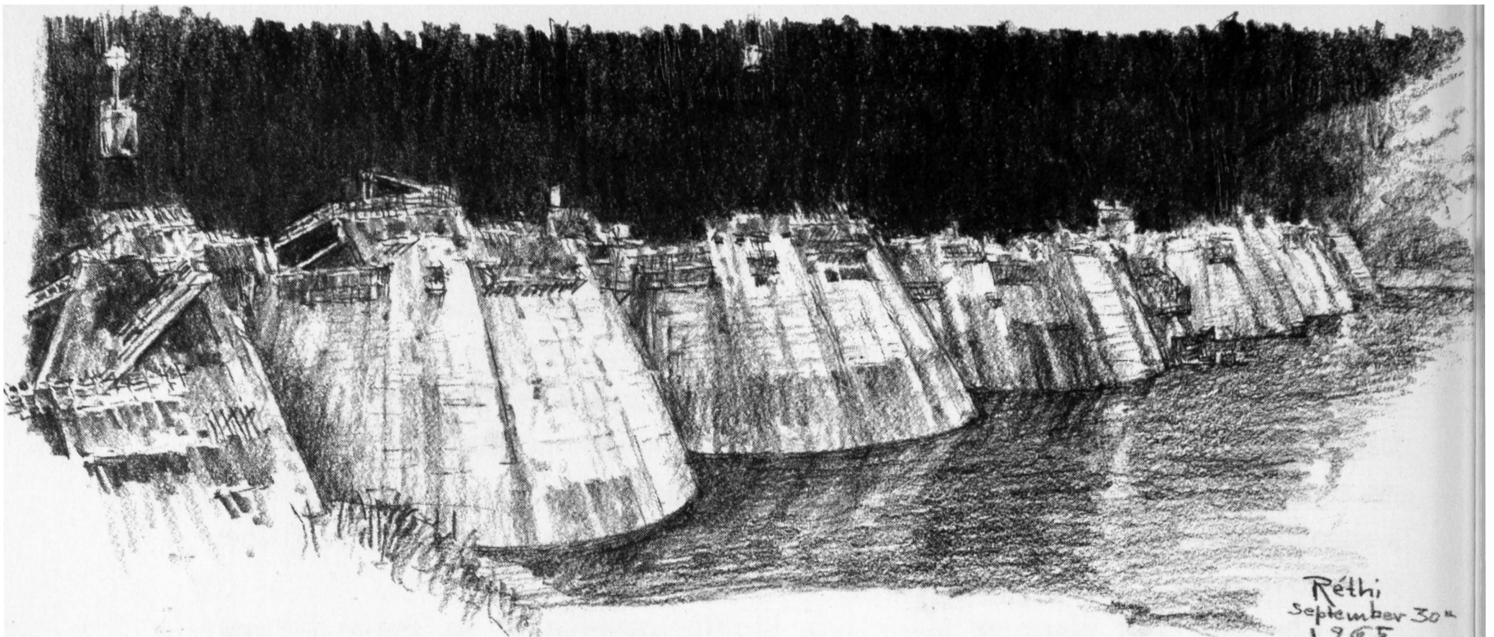
because the incoming sand has too much of one size, the electric valve opens automatically and sends this particular size to the waste pile.”

Once the sand dropped through the electric valve, obviously still mixed with a lot of water, a device called a “screw washer” performed the next job. The screw washer was a conveyor tilted uphill, which looked like a big auger lying in a trough. The auger rotated in the trough, and as the sand and water mixture dropped in at the bottom, the sand was carried up the inclined trough by the worm action of the auger; the water stayed behind. The length of the screw washer determined how much water was removed. At the top of the plant’s three screw washers, the various sands dumped onto a conveyor belt and went out of the plant to a stockpile where it awaited the haul to the dam.

The big sand plant at G-13 was highly automated. Its nerve center was an involved control console in an air-conditioned room. Scores of colored lights flashed off and on as the various scales, belts, and valves did their jobs. Meters and gauges were everywhere. The scene was more suggestive of the block house of a moon-rocket launch pad than a sand plant deep in the bush country. Because of the automation, it took only eight men to run the whole plant and turn out an average 2000 tons per

An autumn sky in 1965 signals the end of another construction season, the biggest ever for Manic 5’s concreters. During the record month, crews place just short of 138,000 cubic yards of concrete to create the vast sculpture that now harnesses the Manicouagan River. Out-of-service diversion tunnel is at lower left.





Around-the-clock operations keep concreters well ahead of rising waters as shorter days keep the lights burning more hours than they are off. As the bush country freezes up for the winter, precipitation turns to snow, stream-flow dwindles and the reservoir fills more slowly.

shift. Manic 5's around-the-clock sand-classification operation required only forty-two men, including truck drivers and other workers.

About twenty trucks hauled the sand the 7 miles from the sand plant to the concrete batch plant at the dam. (These trucks and their drivers were not Hydro-Quebec employees, but rather independents who were hired by Hydro-Quebec on a piece-work basis. The government-owned utility chose this course purposely to provide as much employment as possible for local people.) The trucks carried between 16 and 20 tons, and, since the owners were paid both by the ton and the mile, they had a tendency to overload them.

"There were always a couple of them in the shop with burned-out clutches and engines," said Desrochers. "Apparently, they made enough extra on the overloads to cover this excessive maintenance on their trucks. But, sometimes, I wondered."

While these truckers worried about the quantity of sand their trucks moved each day, a small group of technicians concentrated on the quality of this important component of the concrete. To check the sand's quality, the technicians ran a test called "gradation," using a stack of sieves with various-sized openings, the biggest at the top, the smallest at the bottom. A sample of sand was poured into the top sieve. As a machine shook the sieves, the larger particles stayed in the upper sieves while the finest, near the consistency of face powder, passed all the way through to a pan at the bottom. After a predetermined amount of shaking, the contents of each sieve was

weighed on a highly sensitive laboratory scale. Thus, the technician determined the exact percentage of the various sizes.

Another important test at G-13 was of the moisture content of the sand. Since the amount of water in concrete is critical (the ratio of cement to water must be precise to attain a particular compressive strength), no extra moisture can be allowed in the mixture via the sand. For example, the sand leaving G-13 by truck for the concrete batch plant contained approximately 4 to 6 per cent water. The quantity varied somewhat, depending on the weather for one thing, and last-minute spot checks were made just as the sand went into the concrete mixer. The amount of water added at the batch plant was then directly related to the moisture content of the sand. If the sand was quite wet, for example, the batch plant operator might add only 170 pounds of water per cubic yard of concrete, instead of the normal 190 pounds.

Although building a huge dam in the bush country brings to mind muddy boots, bulldozers, dust, and noise, there are construction men concentrating on precision measurements which make the haute-cuisine chef's "pinch of salt" seem like a sloppy unit of measure. The chef's soufflé may fall; the engineers' dam must not.

Production of sand and rock was a major operation at Manic 5, but in the end all the efforts of the quarry blasters, the men at G-13, the truck drivers hauling to the crusher, the technicians running sieve analyses on sand samples, all this effort focused on the same place—the concrete plant. The batch plant with its four mixers, each capable of turning out 100 cubic yards of concrete per hour, certainly did not look like one of the most important structures on the project.

It was a drab building sheathed in corrugated steel sheeting. It was not really a towering structure, although its nine stories made it the skyscraper of Manic 5. A big covered conveyor belt ramped up to the top of the batch plant from the aggregate washing plant, perched just up the hillside. A smaller conveyor came across from the ice plant about 150 feet off. In a way, the ice plant, although smaller than the batch plant, was more impressive. It had class, somehow. The batch plant looked like a dirty old grain elevator. The idea that 3 million cubic yards of concrete would come out of this unimpressive building to produce the highest multiple-arch dam in the world was sort of appalling.

In all fairness, the batch plant had a lot of competition that distracted one's view on the steep slope. Immediately next to it were the two big silos that held 9000 tons of cement each. And Cliff Barrington's aggregate plant had stacked up a half-dozen huge piles of sand and crushed rock, all of which tended to dwarf the batch plant. Nevertheless, this was where the action was. When construction reached its peak during 1965 and 1966, Manic 5's con-

crete plant would produce 5000 cubic yards each day. It would have a record 6-day week of 33,437 cubic yards; a record 26-day month of 137,557 cubic yards. Between April and October of 1966, it would crank out more than 600,000 cubic yards.

The plant had four mixers to provide flexibility. The operator could run the same mix in all four mixers or produce four different mixes simultaneously, if necessary. For example, he might have to produce dam concrete with the big 6-inch aggregate in two mixers, grit mix with very fine aggregate for tunnel lining in another, and structural concrete with maximum aggregate size of $\frac{3}{4}$ inch in the fourth. On a project the size of Manic 5, many things happen at once; they may all call for concrete at the same time. Of course, concreting on the dam, once it began in 1962, never stopped until the summer of 1968 (except for weekends and the winter shutdown).

Manic's batch plant was a semiautomatic unit. The operator had a console which showed on a dial precisely what was going into each batch. For instance, to make a typical cubic yard, the dial reads zero; at the push of a button an air valve opens a gate and 3- to 6-inch aggregate falls into a hopper suspended so that a scale records the weight of its contents. When the scale dial reads 900 pounds, that gate closes and the gate under the $1\frac{1}{2}$ - to 3-inch aggregate opens to dump 695 pounds of that size from the bin high overhead. Just as the dial approaches 1595 pounds (900 plus 695), that gate closes and a third opens. This process continues: 440 pounds of $\frac{3}{4}$ - to $1\frac{1}{2}$ -inch aggregate; 250 pounds of $\frac{3}{8}$ - to $\frac{3}{4}$ -inch aggregate, 695 pounds of coarse sand; 530 pounds of fine sand; 394 pounds of cement; 190 pounds of water; and 10 to 19 ounces of a chemical air-entraining agent. The 4094-pound recipe is complete; a chute is directed at the gaping mouth of one of the mixers and the ingredients for one cubic yard of concrete are churned in the rotating barrow until it's thoroughly mixed. Actually, this recipe is multiplied by four, since each mixer handles 4 cubic yards. But still the dusty old batch plant had to repeat this operation hundreds of thousands of times to build Manic 5.

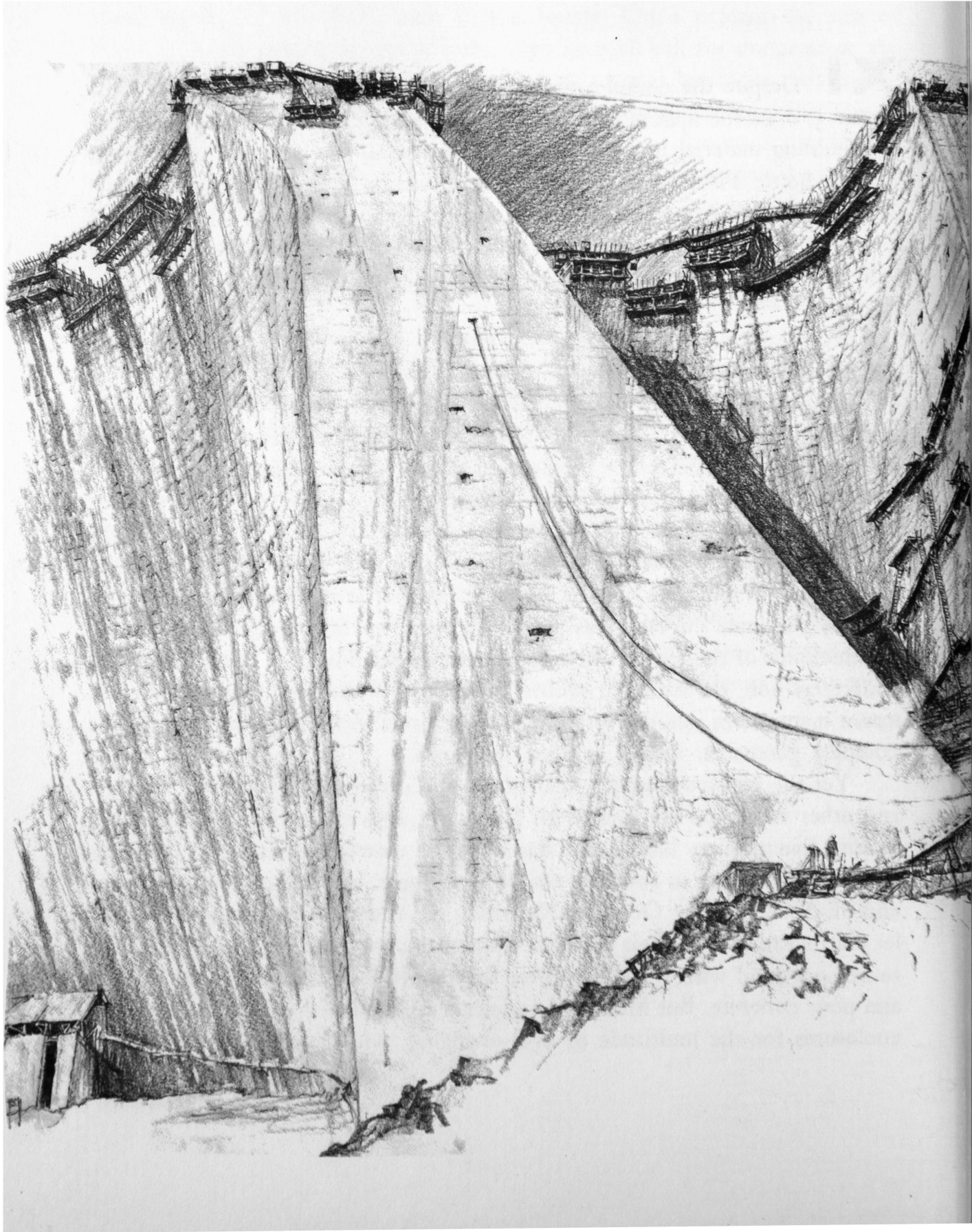
XI Despite the complexities of mixing concrete for a dam the size of Manic 5, once the operation is set up and operating the actual production of the building material becomes routine. But mixing the concrete is not even half the battle. Placing it to create the structure is the major operation. Since Manic 5 was not just a routine gravity dam with a vertical upstream face and a sloping downstream face, both faces running in a straight line across the valley, concrete placement was an engineering challenge of staggering proportions.

To create on paper the graceful curving arches, leaning on their triangular buttresses, was one thing. But actually molding the complicated geometry of Manic 5 involved casting more than 8000 individual blocks, with an average volume of 250 cubic yards per block. And although all but the three arches near the center of the dam were fundamentally the same, each block represented a separate little solid geometry problem. Manic 5 was not simply a case of placing one block atop another. Each so-called lift might be 5 feet high, but rarely was there more than one set of parallel vertical faces. The curved faces, on the up- and downstream sides, although having roughly the same curvature as they rose, were never truly parallel because the thickness of the arches diminished with height. Further complicating the concreters' job, the string of arches, as compared with one continuous arch, meant many more joinings of arch configurations with buttresses, making for complex geometric shapes at these junctures.

Yet the construction plan called for the carpenters, plumbers, welders, and other workmen involved with formwork and concreting to place from twenty-five to thirty blocks each day. And the weather at Manic 5 limited the concrete placement to roughly 140 days per year, extending from about the end of April to early October. Normally the resourceful Canadians do not let cold weather stop their concrete operations; they simply enclose the area to be concreted with wood or plastic sheeting, heat it with steam or hot air, and pour concrete. But Manic 5's engineers concluded that building separate enclosures for the multitude of ever-changing, odd-shaped pours would be

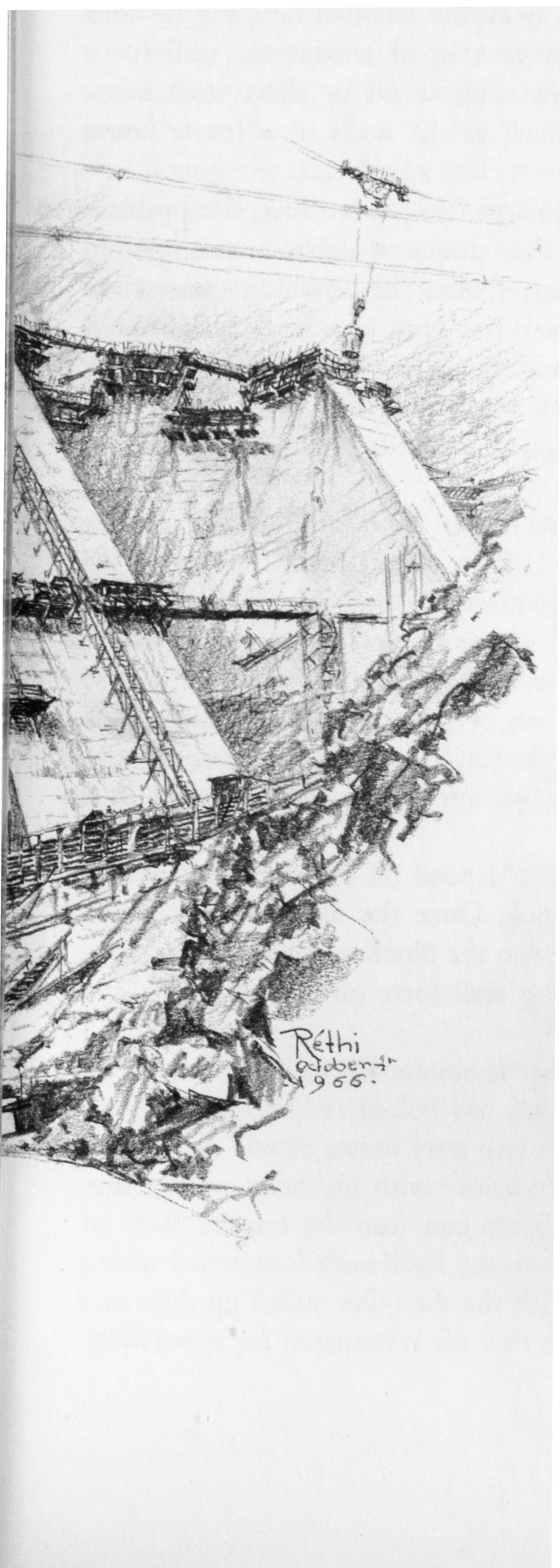
prohibitively expensive. Besides, the reservoir would take eight years to fill by the best estimates. If everything could be kept on schedule, the dam could be completed by 1968 and kept ahead of the rising waters behind it through the ensuing years between 1962 and 1968.

What might be considered the first bucket of concrete for the dam itself was placed in the fall of 1962. This was a relatively easy operation, filling the deep slot in the gorge beneath the main arch. This work area was enclosed



and heated, and concreting was carried out through the winter of 1962-63. The formwork was simple, mainly comprised of two vertical walls running 90 degrees to the gorge, the rock walls of the gorge serving as the other two sides of the mold for the block.

At this juncture, a brief discussion of concrete forms is essential. The simplest type of formwork to describe would be that for a block of concrete, for example, 2 feet square. This could be done by constructing a



Main buttress has reached awesome proportions by 1966 (note man at base). Outlet control works at lower left, two years earlier a rather impressive structure, now looks like a shanty huddling in curve of arch.

simple wooden box, with its inside dimensions $24 \times 24 \times 24$ inches. Now, concrete being a relatively heavy, semiliquid material, this box, or formwork, would have to be substantial enough to prevent the concrete, by its sheer weight alone, from tearing the box apart. This could be done in a variety of ways, such as strapping the box together or bracing its walls on the outside. It could be locked together by wires or bolts between the parallel walls of the box, assuming it did not matter that the finished block had these tie rods permanently embedded. After stripping away the wooden box, the tie rods could be cut off, just as is done in construction of a concrete wall for a building. The actual forms can be made with wood or sheet steel faces, reinforced with beams such as 2×4 , much as the walls of a frame house are constructed.

Now, if this hypothetical block is enlarged to 20×20 feet, the problem of formwork becomes more difficult. The simple wooden box is getting rather large and keeping it from falling apart when filled with concrete is not so easy. True, the same basic principle could be used on a large scale. But if the block is going to remain a cube, standing 20 feet high, the "box" must become a major structure in its own right. In essence, this is the problem the dam builder is confronted with, multiplied a hundred-fold (at Manic 5, 8000-fold).

Although Manic 5's concreters never had to cope with a block 20 feet high, many were more than 20×20 feet in plan. Actually, the height of the blocks in most dams remains relatively constant, dictated by the forms used and other considerations such as curing temperatures (the larger the mass, the slower the curing process). Once the height of the lift is determined—6 feet in Manic 5's main arch and buttresses, 5 feet in the small arches and buttresses—it becomes the common denominator. The term "lift" is said to derive from necessity of lifting the formwork into a new position after each pour.

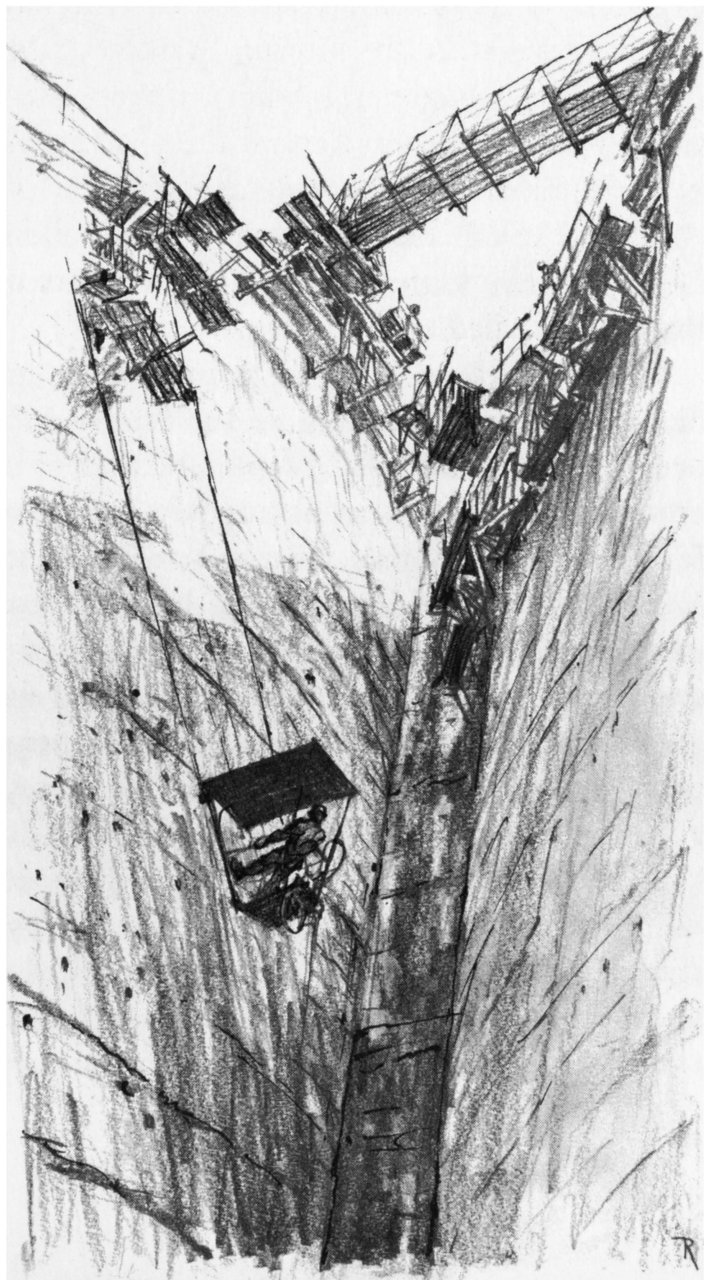
The formwork used on a dam cannot depend on exterior bracing such as we discussed for our hypothetical block. Once the dam rises above the ground, this becomes impractical. And when the block measures 25×60 feet, tying one wall form to its complementing wall form on the other side also becomes impractical.

So dam builders have developed what is commonly called a "cantilever form." Steel beams, usually two per panel, are bolted to the form itself, a flat surface of either wood or steel. These two steel beams extend downward and are bolted to the concrete of the lift below with big bolts called "she-bolts." Steel devices with female threads are cast into the outside faces of the blocks in predetermined locations. Then the formwork is attached with a male threaded unit, a large stud bolt. With the she-bolts pulled up tight and the form panels cantilevering upward, the next lift is prepared for concreting.

Each individual form used at Manic 5 was actually a far more complex unit than that just described. Plywood panels served as the face that contained the fresh concrete and actually shaped the lift. But the plywood was held in place by a steel frame, which in turn was attached to vertical beams. So that these cantilevered beams would not bend under the weight of the concrete, other steel members created a truss. Longitudinal members tied the two trusses together to create an integral unit with a form-face area about 8 feet square. This basic working unit was used throughout the project with many adaptations. Carpenters and welders, by adding triangular sections and narrow strips where needed, made these forms fit the many odd shapes that had to be molded.

Besides the steel frame and trusses, each of these form units had to have work platforms on their outsides from which workers could install and remove the she-bolts. These welded steel and wood scaffolds were used by an assortment of daredevils preparing the formwork. Whereas the workers on the inside of the lift to be poured had their feet on solid concrete, albeit 400

A daredevil suspended high on upstream face near juncture of two arches works on his own private platform far from the "safety" of the catwalk above him.



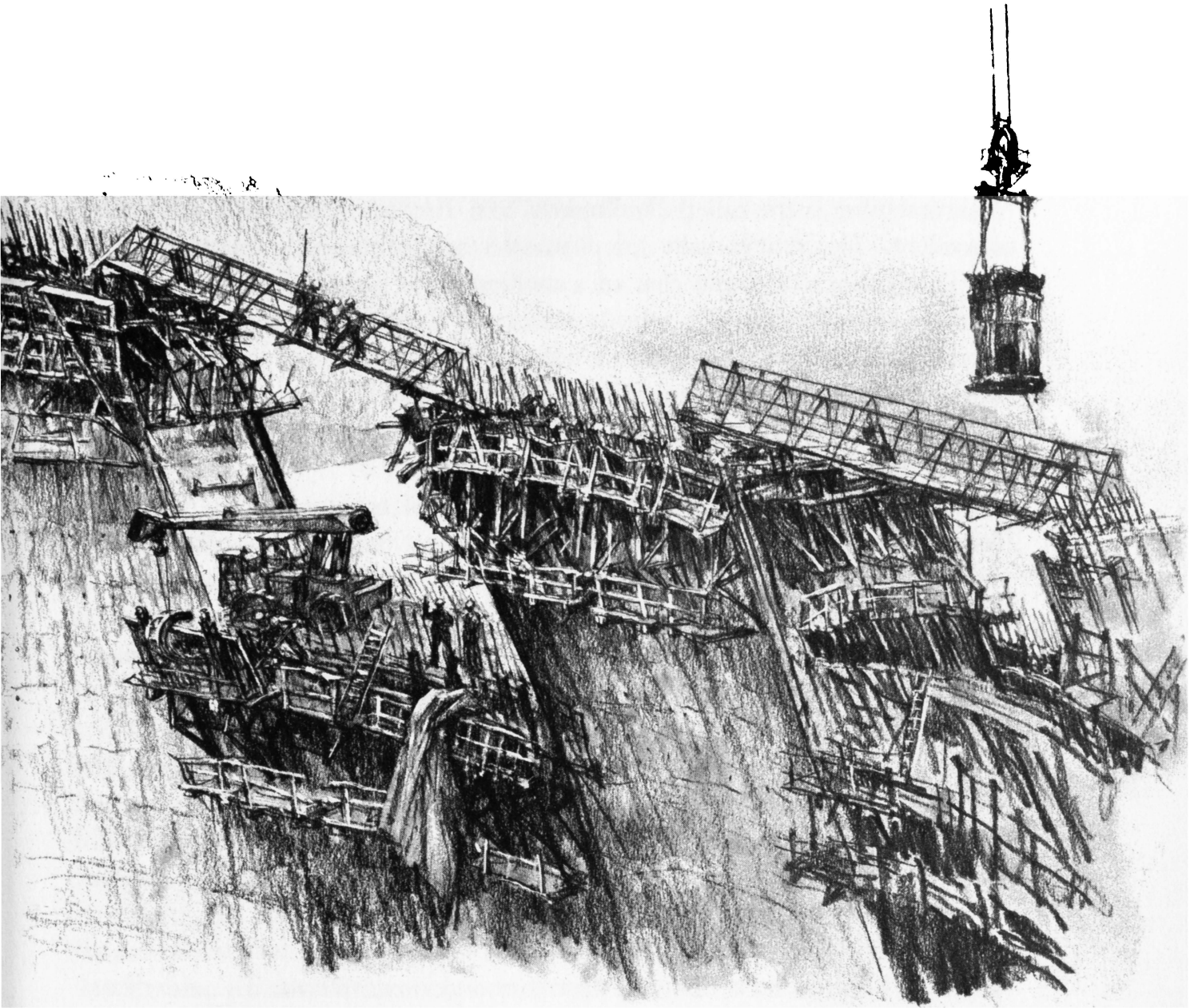
or 500 feet in the air, the men on the outside of the forms had nothing but a couple of wooden planks to stand on and a little railing behind them. No workers were ever allowed on the dam without safety belts, but these men erecting formwork had to be forever moving from one spot to another, climbing around like monkeys, and too much of the time, their belts were of necessity attached only to their waists.

The most precarious formwork on the dam was that for the downstream faces of the arches, the tops of which sloped downstream at a sharp angle. Again, standing inside the lift, the formwork still had a secure look about it even though it leaned outward. But on the outside, the forms angled out over one's head at slopes as great as 70 degrees. So that workers could stand rather than lie on their backs, the work platforms on the outside of these forms cantilevered out away from the dam's concrete face for a disconcerting distance. These men literally were standing in midair. On the upstream side, if one should fall, there was at least a reassuring slope of concrete, a possibility of survival; but on the downstream side, a fall meant certain death.

But like most construction men who work in high places, the French Canadians' philosophical reaction was: "You can fall only 15 feet and kill yourself." (My private response to that has always been: when you fall 500 feet the odds are worse.) Manic 5 workers also used to joke about which side was better for falling. Experience eventually proved that the upstream side was better. Several men had survived after the long slide on the upstream face, but the couple of men who had gone off the downstream side had been killed. But like flying, dam-building is safer than driving automobiles. Many more men died in their cars driving to and from the project than were killed on the dam.

Guy Vachon, Hydro-Quebec's field engineer charged with technical direction of the concreting on the dam and spillway, had far more to worry over than the relatively simple erection of the forms to contain the concrete. But that is not to downgrade form erection, for obviously the forms for each of the dam's thousands of lifts had to be precisely positioned. Vachon's formwork crews were creating concrete sculpture, but unlike the studio sculptor's work, this massive work of art was not a product of anyone's imagination. Engineers' slide rules and electronic computers had dictated every subtle curve and slope. The carpenters and welders, placing a form panel, took their measurements from surveyors' control points placed on adjacent blocks.

The survey crews had spotted these control points with instruments using simple but very precise triangulation from fixed reference points on the river banks. The computer in Montreal had calculated in advance the exact location of every control point and the offset distance to the top four corners of every lift in the dam. So the survey crew chief, using printout



Hydraulic crane, affectionately dubbed a “bullmoose” by workers, helps to raise formwork in one lift as bucket of concrete arrives for another. Precarious catwalks used to cross between blocks are shifted by cableways.

sheets from the computer, could establish these control points in minutes. The form crews measured the offsets from these marks to establish the position of the forms for each lift. There was naturally some margin for error, since the forms sometimes moved slightly when subjected to the great weight of the concrete. But because of the constant checking by the survey teams, these variations were easily compensated for on the next lift.

Long before a bucket of concrete arrived at a particular lift, Vachon’s crews began preparations. There was much to be done. The forms had to be raised and this was usually done with the aid of a “bullmoose.” “Bullmoose” was the name given to the versatile hydraulic cranes—squat, fairly small machines mounted on rubber tires. They were powered by diesel or gasoline

engines that propelled them and ran hydraulic pumps for raising, lowering, and extending their booms. There were three sizes of bullmoose, with lifting capacities of 7, 8, and 12 tons. (Incidentally, no one seemed to know why these machines were called “bullmoose,” an English word with no French equivalent. The cranes bore no physical resemblance to a moose.)

Despite its size, about that of a medium-sized truck, the bullmoose had far more mobility than its wheels indicated. Each had lifting eyes welded to its frame, and with a couple of wire-rope slings, the big aerial cableways would pick up a bullmoose and plop it down anywhere it was needed, high atop the dam, down in a hole. The bullmoose was the workhorse at Manic 5, and especially so for the formwork men.

The bullmoose was usually the first piece of equipment to arrive on a freshly poured block (forms were never stripped until the concrete had set for a minimum of twenty-four hours). With the bullmoose in position on the block, workers attached the crane’s hook to steel lifting-slings secured to a form section. Then the daredevils clambered out onto the scaffolding and loosened the she-bolts with air-operated wrenches similar to those used on wheel lugs in service stations.

With a creaking and scraping of wood and steel against concrete, the bullmoose would raise the formwork slowly upward until it was positioned at the next set of she-bolt holes. The rat-tat-tat of the air wrenches would echo from below and, except for minor adjustments, the panel was in place for the next pour.

Depending on the particular block there might be formwork on all four sides or only on two sides, upstream and downstream. To understand this system, one must visualize each arch as being comprised of eight trapezoidal columns, not vertical, since Manic 5’s arches lean downstream against their buttresses. Dam builders refer to each of these columns as a “monolith”—indicating that it is a continuous pour with no horizontal construction joints.

In actuality, the concreters do stop every 5 feet and raise the forms, but this process is done very rapidly, and air and water hoses rip away at the top of the previous lift to expose green uncured concrete just before the next lift is poured. This process is called “green-cutting.” In principle, and generally in practice, the new lift bonds with the one below it, the curing process still in the early stages in the lower lift continues, and when more concrete is added, the two blocks become one homogeneous mass of concrete with no so-called construction joint.

By contrast, the vertical joints between these columns are construction joints, where no bond is expected. In fact, these joints actually open slightly as the concrete cures and contracts. The vertical joints are keyed together, with large grooves in one face and mating ridges in the other, but there is no

bond between the concrete; each monolith of the arch is an independent structure in a sense. The vertical construction joints are sealed with water-stops and eventually grouted, as will be described later, and when the water of the reservoir puts the arch into compression, these joints are pressed tightly together. In theory, the concrete arch dam functions just as the trapezoidal stones cut by a mason form an archway to support, say, the doorway of a cathedral.

The main 703-foot-high arch had fourteen monoliths, so with eight monoliths in each of the twelve side arches, Vachon had 110 arch monoliths, once all thirteen arches were under way. The buttresses were also divided into monoliths, the number of them diminishing as they grew taller approaching their apex. But at the beginning, one of the smaller buttresses would typically have as many as six monoliths, not counting the massive transitional block where the two arches joined their common buttress. So in the early stage there were another seventy monoliths for Vachon to contend with, making a total of 180. The huge main buttresses, more than 100 feet wide, were three monoliths wide and at their bases eight monoliths long. Including their two huge transitional monoliths, these two buttresses represented another fifty monoliths. And remember that each monolith is made up of scores of lifts each only 5 feet high in the small arches, 6 feet high in the main arch. Before Vachon and his men were done, they would have to construct more than 8000 of these lifts, each a tiny (sometimes not so tiny) project in its own right. All adding up, ultimately, to the highest multiple-arch dam ever built.

To save formwork, dam concreters work on alternate monoliths, raising every other block higher than the ones in between. As mentioned earlier, this means that forms are needed on four sides of only the alternate blocks. The blocks in between thus only require forms on the upstream and downstream faces, the concrete of the blocks on either side serving as forms.

This system called for tight co-ordination and planning for two reasons. First, concrete could not be poured in the low blocks until the high blocks rose to the point where their formwork was clear of the lower lift to be poured. On the other hand, Surveyer, Nenniger & Chênevert, as Hydro-Quebec's consulting engineers, specified that the higher monoliths in the arches could not rise more than three lifts above adjacent blocks. This was because of the 70-degree slope of the arches. If one monolith were built too high, it would cantilever so far out that tensile stresses might develop in the concrete. The thin concrete arches are designed to withstand compressive forces, but have hardly any of the steel reinforcing needed to develop tensile strength. So although the engineers would allow the concreters to build the arches without all the monoliths at the same level, no monolith could get too far ahead of its neighbor.

Hard-hatted workers squirm between reinforcing bars to make last minute adjustments before concrete arrives.



For Guy Vachon, this meant planning his concrete operation with the precision of a chess player. Without careful co-ordination he could check-mate himself—unable to pour this lift, because it had to wait for that one, which in turn could not be poured until another was raised. And worse, readying each lift for concrete involved much more than just raising the formwork.

Once the forms for a lift were in place and the bullmoose was airlifted on to its next perch, a variety of construction tradesmen moved into the lift. Ironworkers and welders came to install the single grid of big steel reinforcing bars placed close to the upstream and downstream faces. This minimal amount of reinforcing (not very minimal in size—the bars were $1\frac{3}{4}$ inch and 1 inch in diameter) played no major structural role. They were designed mainly to prevent microfissuring, tiny surface cracks in the faces which could be caused by the extreme temperature variations at Manic 5.

These reinforcing bars were relatively simple to install since the vertical bars from the previous lift extended up into the lift to be poured. These were merely extended, lift by lift, the horizontal bars wired to the vertical, and the reinforcing in the upstream and downstream faces was ready. Meanwhile, plumbers and pipe fitters swarmed in the lift, busy at a variety of jobs.

If the lift was a lead lift, higher than those on either side, waterstops had to be installed. About 1 foot in from the upstream face, a 30-inch-wide strip of 12-gauge copper formed the first watertight seal across the vertical construction joints. Half its width was embedded in the lead lift, the other half left extending through a crack in the formwork. It would be embedded in the adjacent lift when it rose to that level. About 1 foot behind the copper waterstop, a 2-inch-wide vinyl waterstop was placed to serve as a secondary seal. This thick rubbery strip had a fluted surface, grooves running longitudinally, to assure that it stayed locked in the concrete. A similar vinyl waterstop sealed the construction joint on the downstream face, but its main purpose was not to keep water out, but to keep grout in when the soupy cement mixture was pumped between the monoliths.

This brings up another job the plumbers had to perform in each lift. Small grout pipes extended up through the dam in an elaborate network designed so the vertical construction joint could be grouted in zones. These zones were formed by horizontal waterstops installed every 50 feet, thus dividing the faces of the huge vertical joints into small controllable zones. This meant that steel grout pipes leading to and from each of these zones had to be embedded in the dam as it rose.

The grout crews with their pumps and gauges worked from tunnels, called "galleries," which were built within the dam. There were seven of these inspection galleries, running the length of the dam, vertically spaced about every 100 feet. From these galleries, grout was pumped into the various zones, called "circuits" by the grout technicians. Two pipes, about 1 inch in diameter, led from the gallery to each zone. Grout could be pumped through either one. The liquid discharged into the joint through simple check valves—rubber-like plugs in the pipeline circuit that open under the pressure of the grout, then close when pressure is reduced. These valves, called "clapets," were specially designed so they would reopen if secondary grouting was required.

The construction joint grout circuit was designed with clapets in specific locations so that the grout would be distributed evenly throughout the area defined by the waterstops. Each circuit was so designed that once grout injected through the clapets had found its way into all the voids in the zone, it would then feed back through the discharge side of the circuit back to the grout crews in the gallery.

Once this happened, theoretically that zone had been grouted. The piping circuit could then be flushed with water at lower pressure than the approximately 50 pounds per square inch used by the grouters. This cleaned out the circuit without opening the clapets, thereby making it possible to reuse the system. Once the primary grouting had been completed and allowed to cure for a certain period of time, the same embedded pipeline system was used to test the effectiveness of the grouting job. Water, injected under sufficient pressure to open the clapets, proved whether the joint had been sealed. If a significant amount of water made it through the joint to the return line, the zone would be regouted.

At any rate, this complicated plumbing system had to be extended up through each lift, complete with clapets, collecting and drainage grooves, every component of this system precisely located in the lift. The other workers, going about their various tasks, had to be careful not to bend, dent, or rupture any of this relatively delicate system. One grout pipe pinched shut could make it difficult to seal a whole zone of a construction joint.

Meanwhile, other crews extended water, air, and electrical pipelines, also embedded in the dam, so there would always be an ample supply of each at the working levels. In most lifts, four steel pipes extended upward, parallel to the upstream face, but behind the waterstops. These appeared to be just more pipelines for some purpose or other; their real purpose did not become obvious until right after a lift had been poured. While the concrete was still green, a work crew would come and attach a small chain hoist mounted on a tripod. To my amazement, the first time I watched this operation, they rather effortlessly began pulling the pipe upward. Since I had assumed the pipe ran from the bottom of the dam to the level where we were standing, several hundred feet above ground, this pipe-lifting operation startled me: first, because it did not seem possible; second, because it seemed an illogical thing to do. It was a revelation to find out that these pipes were only about 8 feet long and were jacked up like this with every lift, leaving behind hollow tubes within the dam.

There were four of these tubes cast into each monolith and their purpose was to intercept any leakage that might work through the horizontal joints, which theoretically were not joints. The designers obviously left nothing to theory. If any water did make its way into a joint, these drains would bleed it away in an orderly fashion. Also the water could be carefully measured. This drainage system would serve over the life of the dam. Any sudden increase in seepage from a particular portion of the dam would indicate trouble, and since this drainage system ran down through the dam, passing through a system of inspection galleries, the area where excessive seepage was occurring could be pinpointed and sealed by pumping grout into the troublesome area.

There was even more detail work within each lift before the concrete could be placed. The galleries, mentioned earlier, created more problems in the lifts through which they passed. In the lower lifts of the dam, the inspection galleries naturally had to follow the scalloped configuration of the dam's arches. This meant that complicated wooden forms for the 7×9-foot tunnels had to be placed within the lift, among all the other involved piping and reinforcing.

Since these tunnels were 9 feet high, they always involved more than one lift, with the lower half being formed in one lift, then the arched roof sections built into the next lift up. The galleries required a small amount of reinforcing surrounding them and waterstops had to be placed completely around them where they passed through a vertical construction joint.

Straight stretches of a gallery, such as those through the buttresses, could be formed with relative ease. In fact engineers eventually designed precast concrete arch sections for these galleries. These precast elements were mass-produced in a casting yard along with cylindrical pipe-like sections for vertical shafts to be cast in the dam. When the rectangular lower part of a gallery had been cast in a monolith, workers then placed a row of the precast elements on the fresh pour to form the tunnel's roof. The next lift of concrete buried the tunnel and the precast elements became a part of the monolith. The big saving here in both time and money was the elimination of formwork; nothing had to be removed after the lift was placed.

XII The foregoing aspects of each lift were really only the rough phases; the fine work involved highly technical installations, commonly referred to as "instrumentation." To explain best a dam's instrumentation it might be said that each dam is a research and development experiment. Dam designers start with their slide rules and computers, arrive at a design, and then transform this paper design into a massive concrete structure. But they do not stop there. They want to know as the dam rises and after it is completed whether their mathematics will prove out. Will the temperatures of the concrete rise and then fall as planned? Will the stresses in the concrete structure develop according to formula? Will the foundation rock support the dam? Will the dam move more than the few inches expected when the tremendous forces are created by water hundreds of feet deep?

Every dam is different primarily because every damsite is different, hence the design of each dam is unique. At a quick glance, Manic 5 appears to be simply a string of arches all basically the same except for the big central arch and its two neighbors which necessarily must compensate for the main arch's oblique buttresses. But on close inspection it can be seen that every one of the dam's arches has to conform to different terrain. The buttress's axes are parallel, but their bases are founded in rock at different elevations as the profile of the gorge changes. The arches also rest in rock that may be 30 feet lower on one side than on the other.

So the stresses in each arch, although mathematically similar, must be carefully calculated in relation to the foundation conditions. When considering these stresses, i.e., how strong the concrete must be to withstand the forces it will be subjected to, design engineers also have to take into account other variables. The major ones are the dead weight of the concrete itself; the head of water behind a particular arch (it varies from more than 500 feet to as little as 50 feet); ice pressures; and seasonal temperature changes.

Once these have been calculated and the structure designed, construction begins. At this point one becomes fully aware of the experimental nature of dam design. The designers of Manic 5 had determined that concrete with



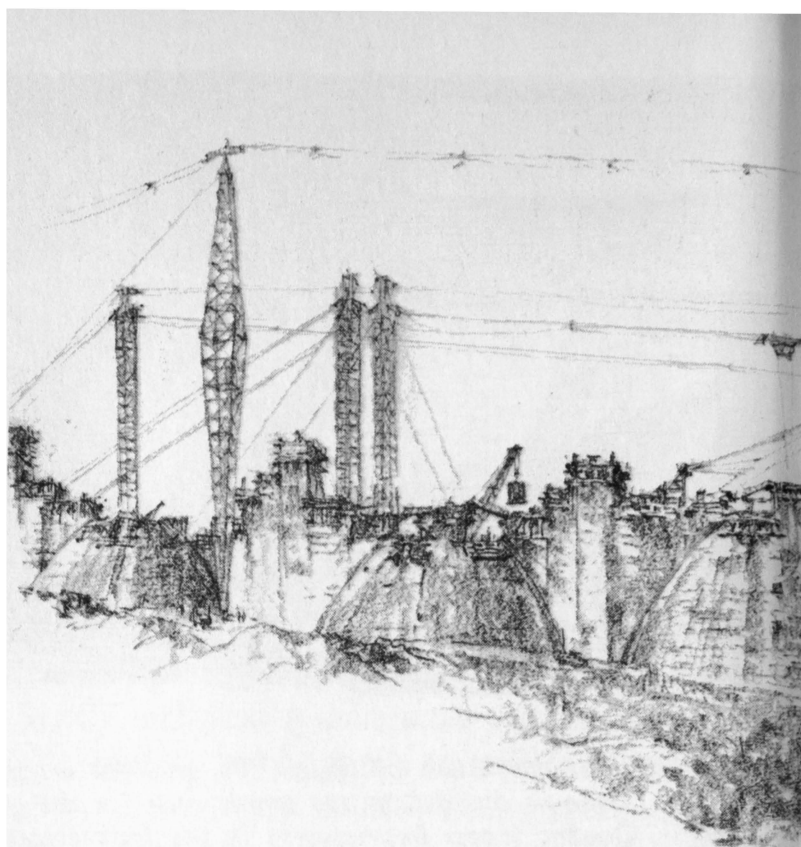
Although much of Manic 5's graceful architecture softens at night, its immense dimensions too much even for the giant floodlights, the pride of Quebec looms impressively in the bush-country darkness.

a compressive strength of 1400 pounds per square inch would be sufficient to withstand all the aforementioned forces. But the concrete used in the dam had a design strength of 4500 pounds per square inch. Asked why, Jean Larouche, resident engineer for the designers, Surveyer, Nenniger & Chênevert, explained: "This is because we still have to admit that laboratory concrete tests are not absolutely representative of mass concrete placed in the field.

"Secondly," said Larouche, "we can only predict the behavior of the dam and foundation with some approximation. Many factors contribute to this. Theoretical stress analyses are based on ideal solids with known homogeneity, isotropic properties, and elastic behavior. The concrete placed in the field is not always ideal.

"The order and rhythm of concreting affects many things as do the temperature variations over the construction period," he said. "Not only is the concrete's heterogeneity inconsistent, but so is that of the foundation rock. And the cooling of the concrete in a dam, despite careful control, is also bound to vary in different parts of the structure. Also because of the many years needed to fill the reservoir behind Manic 5, impoundment would begin before the dam is completed; it's one thing to compute the stresses that will develop on the completed structure with a full reservoir, but what would happen to a half-finished arch with the reservoir one-third full?"

Because of all these problems the designers of Manic 5 were busy with many things besides supervising construction. While making sure that the



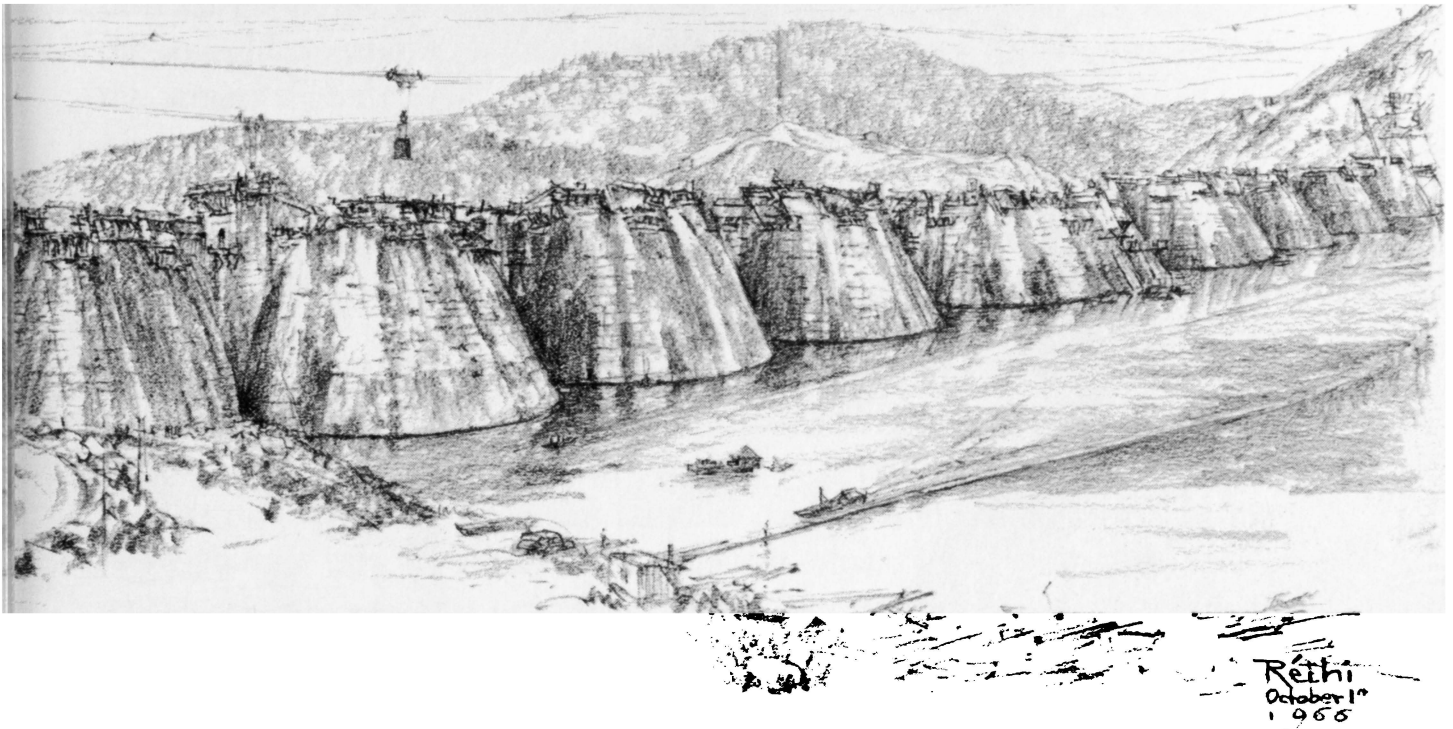
Upstream view from east shore of reservoir reveals vertical gravity portion of structure that ultimately will straddle all the arches as they close. Downstream face of this so-called crest section conforms with slope of buttresses.

construction men built the dam just as it was designed, the engineers and geologists kept checking their design as work proceeded. Would the dam and its foundation behave as planned? To find out Jean Larouche and a staff that numbered as high as forty-five engineers, geologists, surveyors, and other technicians concentrated on four main areas.

They measured the temperature of the concrete after it was placed; the flow and pressure of water entering an elaborate system of drainage holes drilled in the dam's foundation rock and cast in the concrete itself; local deformations within the dam itself; and deformations of the entire structure, i.e., horizontal and vertical movement of the dam and its rock foundation.

To measure these, Manic 5 was instrumented much the way an astronaut's body is wired up when he goes into space. The experts were not taking the dam's pulse or blood pressure, but they did install more than 1000 thermocouples (electronic devices that record temperatures), more than 1200 extensometers (stress-measuring instruments), and a dozen or so huge plumb lines (long wires with weights attached, like a mason's plumb bob), and hundreds of piezometers for measuring pressures.

So the men pouring the thousands of lifts of concrete had these many measuring devices to cope with along with the reinforcing, grout pipes,



flashing, drainage holes, and air, water, and electrical lines, all of which had to be cast into the concrete. Circuits from the thermocouples, spotted at predetermined locations throughout the structure led to central locations in the various galleries so technicians could take many readings at each station. Special reading rooms were built into the dam where the delicate extensometers' gauges could also be centrally read.

Like the grout pipes, these measuring instruments were delicate and workers in the lifts had to exercise care not to damage either the instruments or their circuits. The thermocouples, technically called "thermoelectric couples," are small units made up from two pieces of dissimilar metal, such as copper and iron or bismuth and antimony. When the heat of hydration in the concrete warms the junction between the two metals, a tiny electric current is generated and can be recorded by a galvanometer.

The extensometer, used to measure local deformation in the concrete mass, is a small cylinder about 1 inch in diameter and 10 inches long. It has flanges on each end to anchor the ends of the meter in the surrounding concrete. Inside the cylinder is a length of music wire about 8 inches long attached to each end of the cylinder and pre-tensioned to a known value in the laboratory. Stresses in the concrete will accordingly affect the wire



Nellie
1900

Straight up from within the irregularly shaped arch next to the central arch, the view is both dizzying and incredible. The immediate impression is that the engineers have made some terrible miscalculation.

tension and consequently the frequency of vibration of the wire. The cylinder also contains two small electromagnets, one to put the wire into vibration, the other to transmit by induction the frequency of vibration. Instruments in the reading room within the dam compare the vibrations of the embedded meter with that of identical non-embedded meters and record the strains directly with a precision of 5 micromillimeters per meter. At Manic 5 readings were taken from the hundreds of extensometers about once each month.

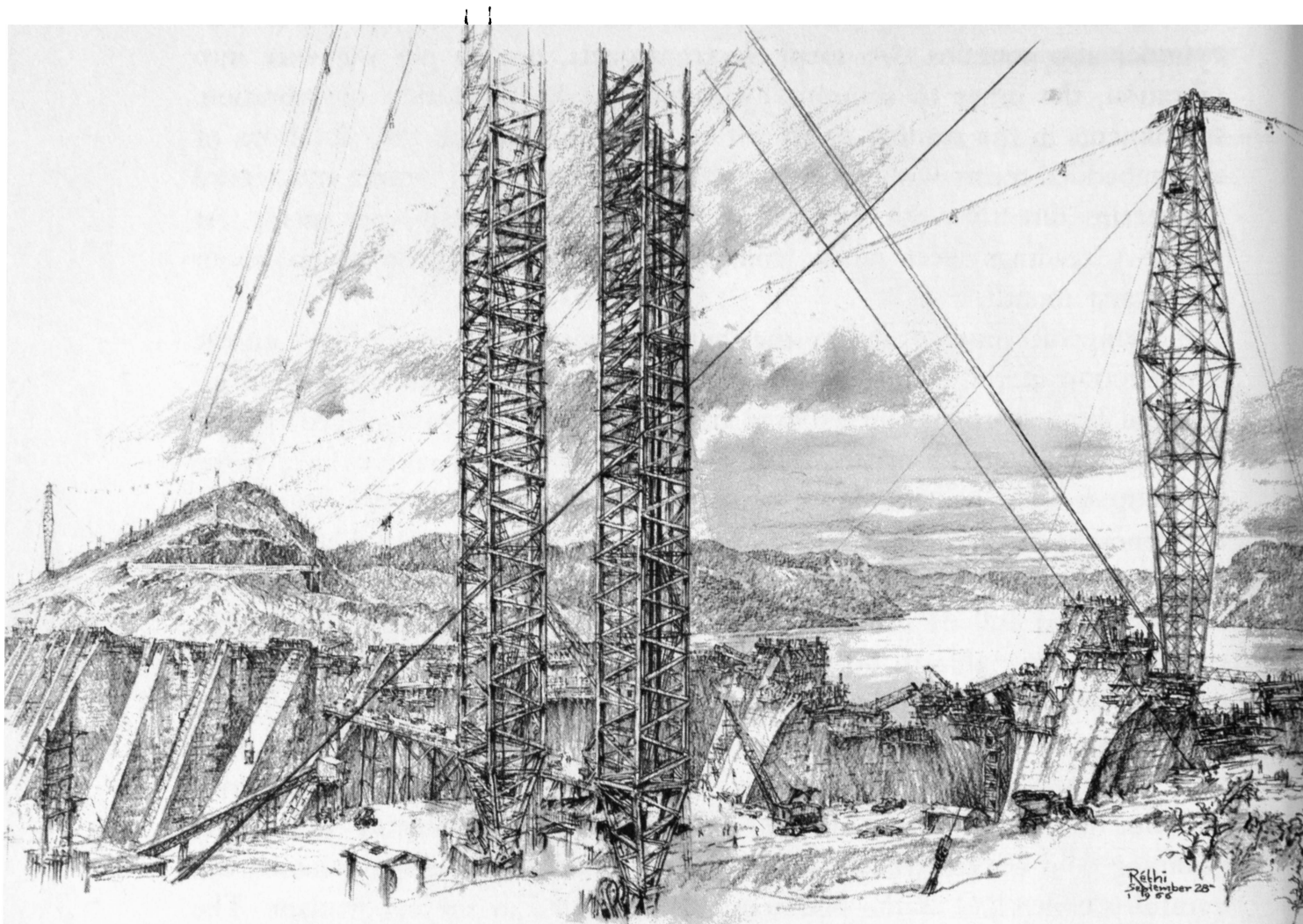
Temperatures recorded by the thermocouples had a direct effect on the construction of the dam. They helped determine the length of time an individual lift had to remain exposed before the next lift was placed. In the main arch and all the massive buttresses, the lower lifts would have taken too long to cool, so they were cooled artificially by embedding tubing in the concrete and circulating river water through this network. The thermocouples told engineers when this artificial cooling could be stopped and the tubes pumped full of grout. By continuous observations, Jean Larouche's technicians were able to determine, as the dam got thinner, when artificial cooling could be discontinued altogether.

"We eventually developed a rule of thumb," said Larouche, "that once wall thickness reduced to 45 feet, cooling pipes became unnecessary."

But this temperature-control problem was far more complex than simply pumping cold water through the embedded tubes. The mix temperature was carefully controlled as the concrete was produced in the batch plant. The design mix temperature called for was 50 degrees Fahrenheit, which was not too difficult to maintain during the cool spring and fall months. But however brief, summer does come to Manic 5, and when the thermometer soared up into the 70s the concrete batch plant operator had to call on the iceman.

Manic 5's iceman ran an operation worthy of many a small-town ice-house of a bygone era. The refrigeration plant had a rated capacity of 200 tons per day and it did not just freeze blocks of ice—the batch plant could not use blocks or even cubes, but, rather, required shaved ice. To make this, the ice plant had two big cylindrical tanks whose walls were refrigerated. Water, sprayed down the inside of the metal walls, froze in a thin film, then was shaved off the walls by rotating blades similar to those in an old-fashioned ice-cream freezer. The shaved ice accumulated in hoppers and was fed to the concrete plant as needed via a covered screw conveyor.

To maintain the 50-degree temperature of the fresh concrete, as much as 70 pounds of ice per cubic yard were added on the hottest days. The batch plant operator had to reduce the amount of water in the mix accordingly, to maintain the specified water-cement ratio. In fact, this very ratio in the Manic 5 concrete was one of the reasons temperature control was so important.



Some monoliths of dam are nearing crest level as easterly arches on high ground promise to be the first closed, probably by 1967. Two head towers for cableways reach skyward in foreground. Odd-shaped tower supports floodlight suspension system.

Because of the high strength that the concrete required—4500 pounds per square inch—the amount of cement per cubic yard was unusually large for mass concrete. Initially, Manic 5's concrete contained five bags (87.5 pounds each) of cement per cubic yard. Because the cement content of concrete has a direct bearing on the heat of hydration (the more cement, the more heat developed), Manic 5's concrete presented difficulties right off. Since designers were aware of this, they specified that a low-heat cement be used. This cement, known as "Type II cement," had a heat of hydration of 65 calories per grain, but its use meant that the dam's designers had to cope with a corollary characteristic. Low-heat cement delays the curing time of concrete, and at Manic 5 the mix used would not attain its full strength for ninety days, which is about three times longer than most concrete takes to cure.

But the dam designers reasoned that the structure would not be subjected to any appreciable stresses until long after this three-month curing period—a valid assumption considering that Manic 5's reservoir would take possibly eight years to fill. Even with starting to impound water in 1964, as they did, it would be 1972 before the dam really had to perform its assigned task. And by holding down this heat generation, the concrete crews could make better time. They would not have to wait so long between placing successive lifts.

Actually there was very little waiting around at Manic 5. The din of the huge construction job never really stopped. Day and night the powerful whine of the big diesel trucks, laboring up and down the steep haul roads, echoed across the gorge. The cableway carriages moved back and forth on their highlines, taking bucket after bucket of concrete to the crews atop the dam. Production was the word—mass production of concrete. Quantity always seemed the most important objective. But inconspicuously there was a small band of engineers and technicians devoting all their time to quality.

The designers had calculated the concrete specifications, the concrete and aggregate plants did their best to make the concrete conform to these specifications, but the men of Les Laboratoires Industriels & Commerciaux Limitées were the real overseers of concrete. Hydro-Quebec engaged this private company to make absolutely sure that Manic 5's concrete was always top quality.

Frederic McGowan headed up this group of about fifty men who did everything from inspect the formwork before concrete was poured to running sieve analyses on the sand long before it even got to the concrete batch plant. McGowan and his men were the construction equivalent of the quality control men who monitor industrial mass production of things like automobiles, television sets, and just about every other item needed in today's technological society. Specifically, McGowan was charged with the inspection, testing, and quality control of all concrete at Manic 5, including quality control of the aggregate and sand.

The inspectors from the concrete laboratory were not only concerned with the physical quality of the concrete itself. McGowan's men inspected the forms prior to pouring, looking for reinforcing bars that were not clean, oil or grease that might have been spilled in the lift, anything that would adversely affect the quality of the concrete. The concrete inspectors were not responsible for the alignment of the forms or the placement of reinforcing steel. These things were the concern of the consulting engineers and Hydro-Quebec. But McGowan's lab certified that each lift was ready for concrete, reporting directly to Guy Vachon, Hydro-Quebec's field engineer in charge of concreting.

Vachon's office each day published a pouring schedule that was distrib-

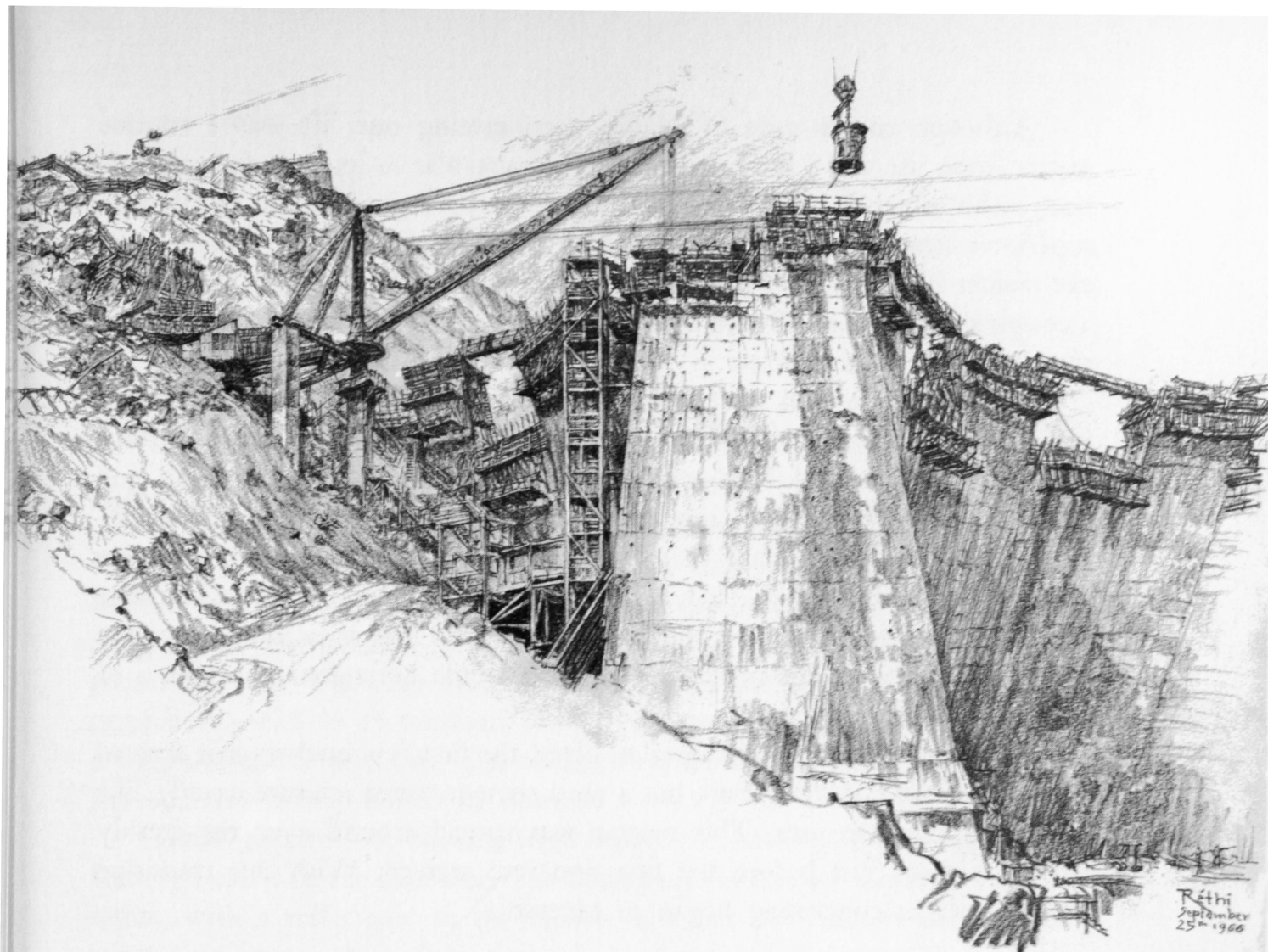
uted to all departments concerned with dam concreting. This schedule was developed from reports submitted from the various departments preparing the forms and, of course, the concrete laboratory. And despite a fairly casual atmosphere, Vachon's office had an excitement about it. Here was the nerve center, two-way radio chattering constantly. Almost like a war room, this was where each day's plan of attack developed. And it took real planning.

Vachon did not simply say: "Well, these twenty-three lifts are ready, so pour in this one, that one, and then . . ." There were myriad things to consider. Some of the logistics involved simple horse sense. There were three cableways, all of which worked simultaneously, but the schedule of lifts to be poured had to be set up so that the cableways did not conflict with each other. The mobile tail towers on the west end of the dam could move in such a way that one would pass over the other, but for obvious reasons this criss-crossing of the main gutlines was never allowed. These were no clothes-lines; the huge steel pulley systems with their buckets carrying 16 tons of concrete must not get snarled up.

So as the daily pouring sequence was developed, each cableway had to be separately scheduled in relation to what the other two were doing. To cope with this, Vachon had a big-plan view of the dam which, incidentally, had to be constantly changed as the dam changed. Colored strings stretched across the drawing represented the highlines and could be moved to plot the day's work.

The cableways had been placed so they could service as much of the 4300-foot-long dam as possible, but since the east end of the dam was a relatively low section of gravity concrete, it was decided that a short construction trestle built just downstream of the dam's axis could carry a revolving gantry crane that would place concrete for that end of the dam. This made it possible to hold the cableways' span across the gorge to a practical yet still spectacular 3700 feet. There was also a short stretch at the west abutment, involving one arch and two buttresses, which was not serviceable by the highlines. To pour that concrete, engineers designed a concrete pedestal that was built between these two buttresses. A revolving gate-leg crane mounted on this pedestal handled truck-delivered concrete at the west end until that part of the dam was completed in 1966.

So during the early years Vachon actually had five different means of delivering concrete simultaneously. Concreters could work in five lifts at one time, each one requiring several hundred cubic yards of concrete. Given ideal conditions with no trouble anywhere throughout the cycles, a single cableway could deliver close to 100 cubic yards an hour, but the planners had to throw in margin factors in their timing, since on a project of this scale there was always room for trouble.



Because a short section of the dam at the west end cannot be reached by the cableways, a gate-leg derrick places concrete delivered by trucks.

And there was another factor in this pouring schedule. Although a lift might be ready to pour, the procedure might not be permitted because the monoliths on either side were not high enough. From the beginning until 1966, the concreters were allowed a four and one-half lift discrepancy between alternate blocks. But as the dam rose higher this was cut back to three and one-half lifts.

Vachon made it sound easy. "We know that steel and drainage take about two hours," he said. "So if I want it for tonight, I schedule it." When the pouring schedule came out, the crews who had to install the reinforcing steel and drainage pipes knew they had to get it done that day so the lift would be ready for concrete that night. Everyone involved, from McGowan's inspector to the cableway operator, knew where he would be working that night. The schedule told the cableway operator the relative location and elevation of the specific lift, although he would get his specific instructions from a radioman on the lift.

Although to the men of Manic 5 concreting one lift was a routine matter, each lift was a little construction spectacular in its own right, which back in Montreal or New York would have drawn a good crowd of sidewalk superintendents. Even before the first bucket of concrete arrived, the excitement began. Under the watchful eye of one McGowan's inspectors, a couple of men worked with high-pressure hoses, apparently washing down the surface of the concrete.

Actually these men were doing more than washing the concrete. They were green-cutting, as mentioned earlier: blasting away at the rough surface with a combination of high-pressure water and air designed to clean and also tear away any weak or otherwise poor concrete. In essence, the green-cutting prepares the surface of the preceding lift, exposing green concrete (usually only a few days old), which has not completely cured. The idea here is to make as perfect a bond between the two lifts as possible, since the vertical monolith is, theoretically at least, a single homogeneous column of concrete.

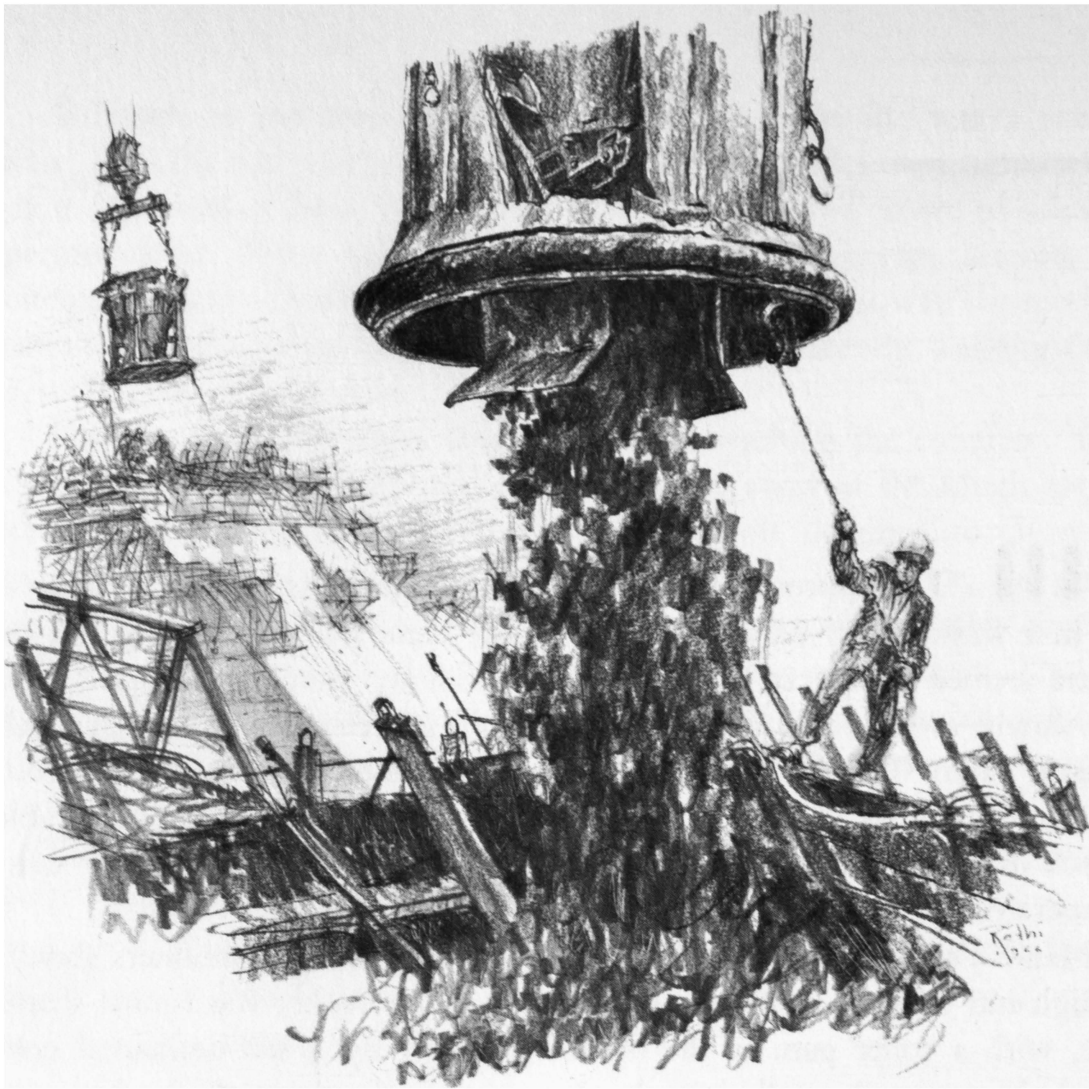
To assure that this bonding takes place, the first few buckets that arrived did not contain concrete at all, but a sand-cement-water mixture exactly like that a brick mason uses. This mortar was spread around over the freshly washed surface just before the first concrete arrived. With this transition layer in place, concreting began in earnest.

XIII The approach of the big concrete buckets was an eerie spectacle in a way. When you were high on the dam, you felt remote and the buckets seemed to appear from nowhere—suddenly looming overhead, lowering slowly as the radio dispatcher chattered in French into his hand-held transistor radio. The men in the lift kept their distance as a bucket gently came down with its 16-ton load. Despite the size of the main support cable, a 3-inch-diameter wire rope, the bucket yo-yoed up and down slightly when the operator finally halted its descent.

Manic 5's concrete buckets were roughly cylindrical containers about 9 feet high and 5 feet in diameter. The bottom of the bucket was funnel-shaped inside, with a roller gate at the mouth operated by a self-contained compressed-air system. A small air tank, charged periodically at the loading area, supplied air to the double-acting pneumatic rams that opened and closed the gate. The system appeared to illustrate the myth of perpetual motion. The air that activated the ram in one direction was not released to the atmosphere when the ram was reversed. Rather it was sent back to the reservoir tank in a closed circuit. This same pressurized air was used over and over, requiring only a bit of make-up air every so often.

In order to empty the big bucket, a worker only had to pull a chain dangling from a small air valve, a far cry from the old-style buckets that were opened and closed manually by operating a big lever. At this point, when the command was given to dump, the cableway operator had to be on his toes. Although he usually could not see either the bucket or the lift being concreted, he would soon have to perform the most delicate part of the operation. Suddenly, without the weight of the concrete, the sag would go out of the main gutline, which would act like a bowstring despite its huge girth.

As the concrete rumbled out of the bucket, the latter would start to rise, and to compensate, the operator would have to slack off on the hoisting cable to keep the bucket roughly at the same elevation until it was empty. Then, as soon as it emptied, he had to raise it up rapidly to compensate as the gutline vibrated downward again. In other words, he would try to



Worker pulls a small chain and compressed air opens a bucket's gated bottom, dumping 16 tons of concrete into the formwork atop the dam. At rear, another bucket arrives at a neighboring lift.

dampen this vibration and keep the bucket from returning dangerously into the lift where the men were working.

One of the reasons dam concreters avoid the word “pour” became evident as the 8 cubic yards of concrete rumbled out of the bucket. The mass concrete used for dams does not pour. It is a very dry mix, called “no-slump concrete,” which to the uninitiated looks like a pile of dirt and rocks. And some of the coarse aggregate is just that—rocks up to 6 inches in diameter. However, the “dirt” is anything but. Fred McGowan’s men saw to it that it was a carefully controlled mixture of sand, cement, and finer crushed rock.

Four times each day, McGowan’s men took samples—about 1 cubic yard, picked at random by an inspector and delivered to the laboratory by truck. The big dump truck, which normally carried 8 cubic yards of concrete, looked incongruous backing into the laboratory with a sample. Raising its body, the truck dumped the sample directly on the lab’s floor. The lab technicians knew exactly which lift was being poured at the time this sample

was taken at the batch plant, so, in essence the sample came from a particular lift, although it was not taken up on the dam for obvious practical reasons.

Once the sample was on the floor, McGowan's crew would shovel it onto a 2½-inch screen mounted on sawhorses. Three or four men did this initial screening, removing by hand the larger aggregate that would not pass the screen. While banging the large rocks on the screen to shake off as much of the sand and cement as possible, the men made absolutely sure that none of the rocks would pass through the big squares of the screen. These large rocks were removed to make the sample manageable enough to cast test cylinders, 8 inches in diameter and 16 inches high.

These cylinders were made for compression tests, which were representative of the concrete even though the large aggregate had been removed. This had been confirmed, and was periodically reconfirmed, by making huge test prisms—18×18×52 inches, which included all aggregate. These big prisms were tested in a mammoth hydraulic press with a capacity of 1200 metric tons. But working with such huge test specimens was, to say the least, a cumbersome process, and the smaller cylinders proved to be just as dependable monitors of the concrete's strength.

McGowan made twelve of the smaller cylinders from each sample for a total of forty-eight each day. Nine of these were stored in big curing rooms, kept relatively warm and humid with steam and water. Three were tested after seven days, three more after twenty-eight days, and the final three after ninety-one days. Compression tests of concrete involve placing a specimen with a specific cross-sectional area in a hydraulic press. It is then squeezed, or compressed, until it breaks. At Manic 5's lab the technicians used a press with a capacity of 400,000 pounds for the normal-sized cylinders.

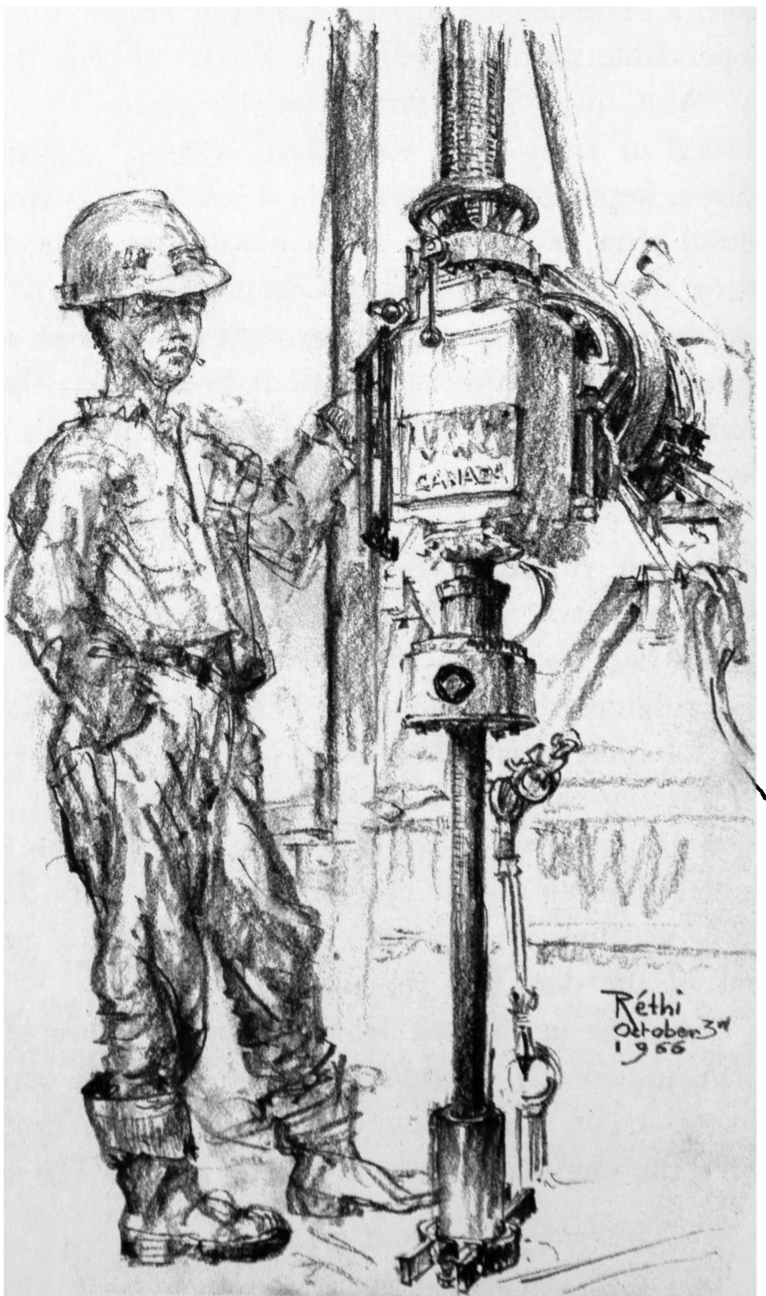
The cylinders were cast in steel molds placed on a table equipped with an electric vibrator. This assured a thoroughly homogeneous sample with no voids, as nearly as possible approximating the concrete placed in the dam, which had also been vibrated with mechanical vibrators. Besides the nine test cylinders from each sample to be stored, McGowan's men had three to use for early tests. These were force-cured somewhat like hard-cooked eggs by placing them in a vat of 170-degree water. The force-cured cylinders were broken after only forty-eight hours, when they were expected to have achieved about 80 per cent of design strength. The idea here was to give an early warning of any bad concrete, so that, if necessary, it could be ripped out of the dam and replaced.

A look at the test lab's log, which showed the performance of more than 40,000 test cylinders just for the dam concrete (not counting about 10,000 taken for concrete used in various tunnels and the powerhouse), gave the engineers little to worry about. The dam concrete was designed

to reach a compressive strength of 4500 pounds per square inch in ninety days. But the log showed that most samples, broken at twenty-eight days, exceeded this; many of those at ninety-one days broke at above 6000 pounds per square inch.

While the cylinders were being made in the lab, one inspector checked the air entrainment—the amount of air introduced into the concrete by adding a chemical agent. (Air-entraining agents are added to concrete mainly to improve its resistance to frost damage.) Two other men took a small sample and tested it for plasticity by placing it in a small vertical cylinder that was vibrated for a given length of time as the concrete flowed out an opening at the bottom. After another sample had partially cured it was tested to determine its specific gravity.

Considering Manic 5's location in a harsh winter climate, the concrete experts wanted reassurances that the concrete would stand up well to repeated



Diamond driller takes one of the thousands of concrete core samples, an important phase of the never-ending laboratory verification of both the performance in the field and the basic design of the dam.

freezing and thawing. To test this quality, hundreds of the big 18-inch-square prisms were placed in covered chambers built into the floor of the lab. For several years at the beginning of the project, these specimens were subjected to hundreds of freezing and thawing cycles until all concerned were satisfied that Manic's concrete would withstand the worst weather northern Quebec could produce.

One year before the dam was topped out, I suggested to Fred McGowan that he sure had taken one hell of a lot of concrete samples over the years. His modest answer: "What about those men bringing in the cement? On a 4000-yard day, I make forty-eight cylinders; they have to provide 18,000 bags of cement."

Besides performing these laboratory tests, McGowan's men had to be up on the dam where the action was. They watched for bad concrete coming from the batch plant, looking for visual clues like too much water in the mix or too much or too little of a particular size of aggregate. The inspectors also checked on the method of placement, although this would seem a fairly cut-and-dried procedure—open the bucket and dump the 16 tons of concrete. What could mere men do with their hands? It was not exactly a shovelable mixture. But McGowan's inspectors were interested in *how* the bucket was dumped. If concrete is dropped too great a distance, it segregates: the large heavier pieces of aggregate tend to go to the bottom with the finer material, including too much of the water-cement paste, staying at the top. The inspectors, therefore, saw to it that the concrete crews brought the bucket within a few feet of the in-place concrete before dumping.

If the crews dump their buckets fairly accurately, there is no need to move the concrete around, but it does have to be worked into many small nooks and crannies in and around all the reinforcing, grout pipes, drains, and gallery forms. There can be no voids or so-called honeycombs. To accomplish this, the men use pneumatic vibrators, odd-looking tubular steel devices resembling blunt-nosed artillery shells, attached to a rubber hose. Actually the vibrator has an air-operated mechanism inside its hollow shell, and when a worker inserts it in fresh concrete, it shakes the mixture and causes it to consolidate, preventing voids from forming. The vibrators also tend to make the stiff mixture flow slightly.

In the early days, Manic 5's concreters were, of course, working in blocks that had larger areas, so they tried using small bulldozers to help move the concrete around. They also mounted several vibrators on the bulldozers so men would not have to strong-arm the heavy units around. But as the lifts got smaller and the volume of concrete in each decreased, the 'dozer-mounted gang vibrators were abandoned. Actually these units still could not get into the tight spots where vibration was particularly critical. A



To prevent voids and produce proper consolidation of fresh concrete, workers manhandle 80-pound pneumatic vibrators as soon as bucket dumps in the formwork.

man had to heave the 80-pound vibrators around regardless, so Vachon eventually gave up using the machines.

Again the inspectors were watching carefully. Excessive vibration is as bad as too little vibration. McGowan's men made sure the concreters vibrated around the reinforcing and up close to the formwork so that the upstream and downstream faces would have a reasonably smooth surface. They made sure the vibrators were not used too zealously, since this can cause the same kind of segregation that occurs when concrete drops too far.

And so the concrete came, hundreds of tons, rumbling into the lift, the vibrators humming and whining, particularly when they touched wood or steel. No matter how many times one watched this spectacle, it was always exciting. The cableways buzzing overhead periodically, making a clacking sound as they picked up and dropped off their slack-carriers, ingenious devices that kept the traveler and hoist cables from sagging too far below the cableway's gutline. (These are similar to the units a housewife places on her pulley clothesline to keep the bottom rope from sagging too much.) On a construction cableway, though, the carriage that rides the main gutline automatically picks the slack-carriers up in front of itself. Each time it grabs one in front it drops off one behind itself.

Climbing out of the lift being concreted, one either had to climb up a ladder to the surface of the adjacent lift, maybe 20 feet higher, or possibly

walk across a small portable footbridge about like a ship's gangplank to the next high block. Clutching the railing of one of these relatively flimsy walkways, one had a choice of looking upstream at the slowly filling reservoir, its dark waters maybe 150 feet below. Or one could look only 20 or 30 feet down to the low lift between the two that the bridge was resting on.

The third view generally called for holding onto both railings with white-knuckled hands. If you happened to be out near the center of the dam, as I was, during 1967, you were probably 600 feet above the ground, and unlike looking out the window of a skyscraper, you were cantilevered out over nothing. It was a sheer drop down to where that 35-ton dump truck looked like a Dinky toy. The only thing big about the truck was the noise from its screaming diesel engine. The nine-story concrete plant looked dwarfed; it no longer dominated the campsite. In fact, the entire construction camp for more than 3000 workers looked as if it belonged under a Christmas tree. You moved gingerly from the catwalk, watching your feet. It was good to be back on solid concrete.

There was nobody in this lift, and you were glad. They might have detected your edginess out there on the catwalk. After a moment to compose yourself, you clambered down into another lift, where there was some activity. A lone welder was tacking a brace made from a piece of reinforcing steel to another short piece, inserted like a peg into the concrete. The brace would steady a form panel and become embedded in the lift's concrete when it was cast.

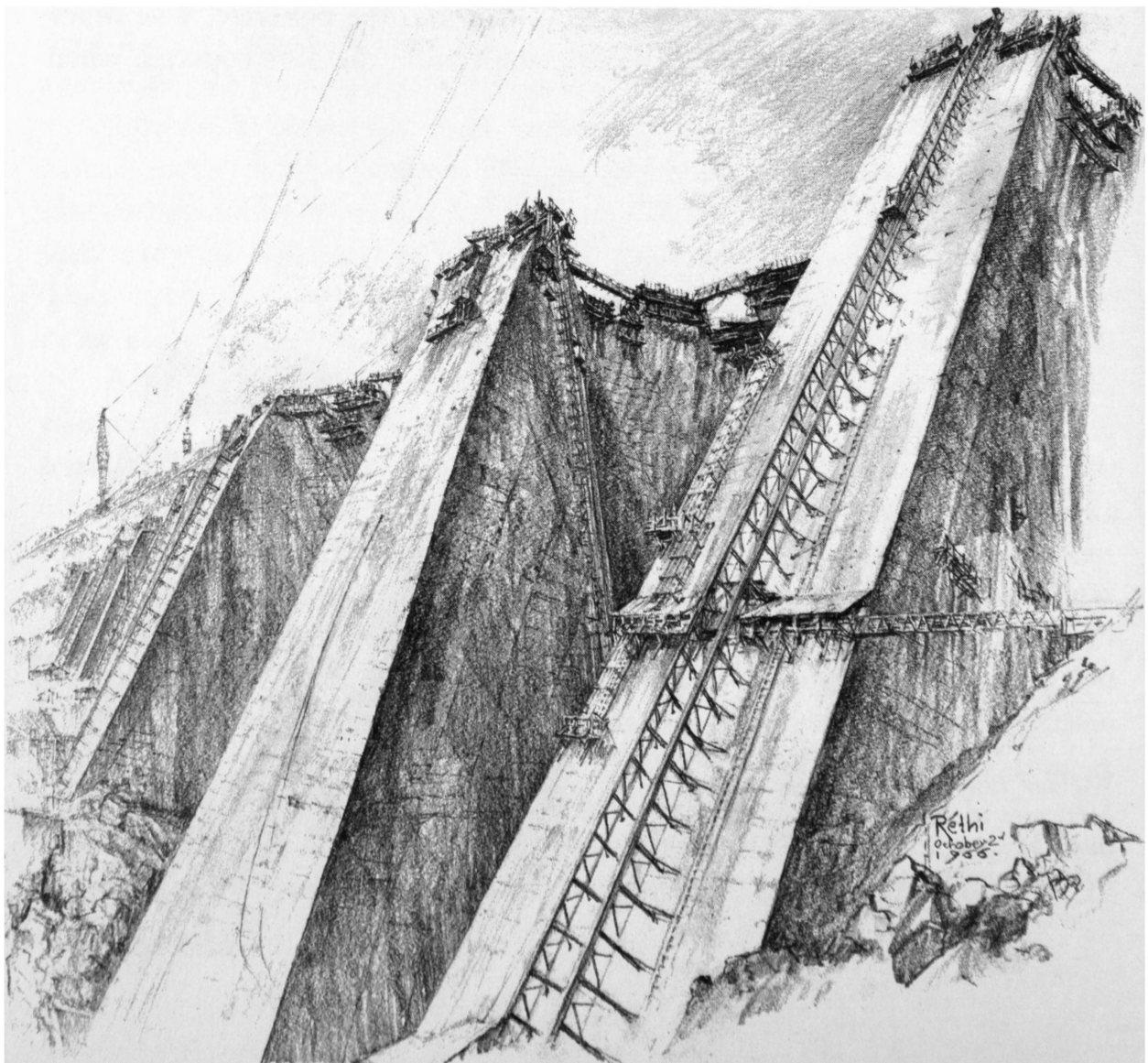
Welder fastens heavy reinforcing bars, one of many details that must be completed in each lift before concrete is placed.

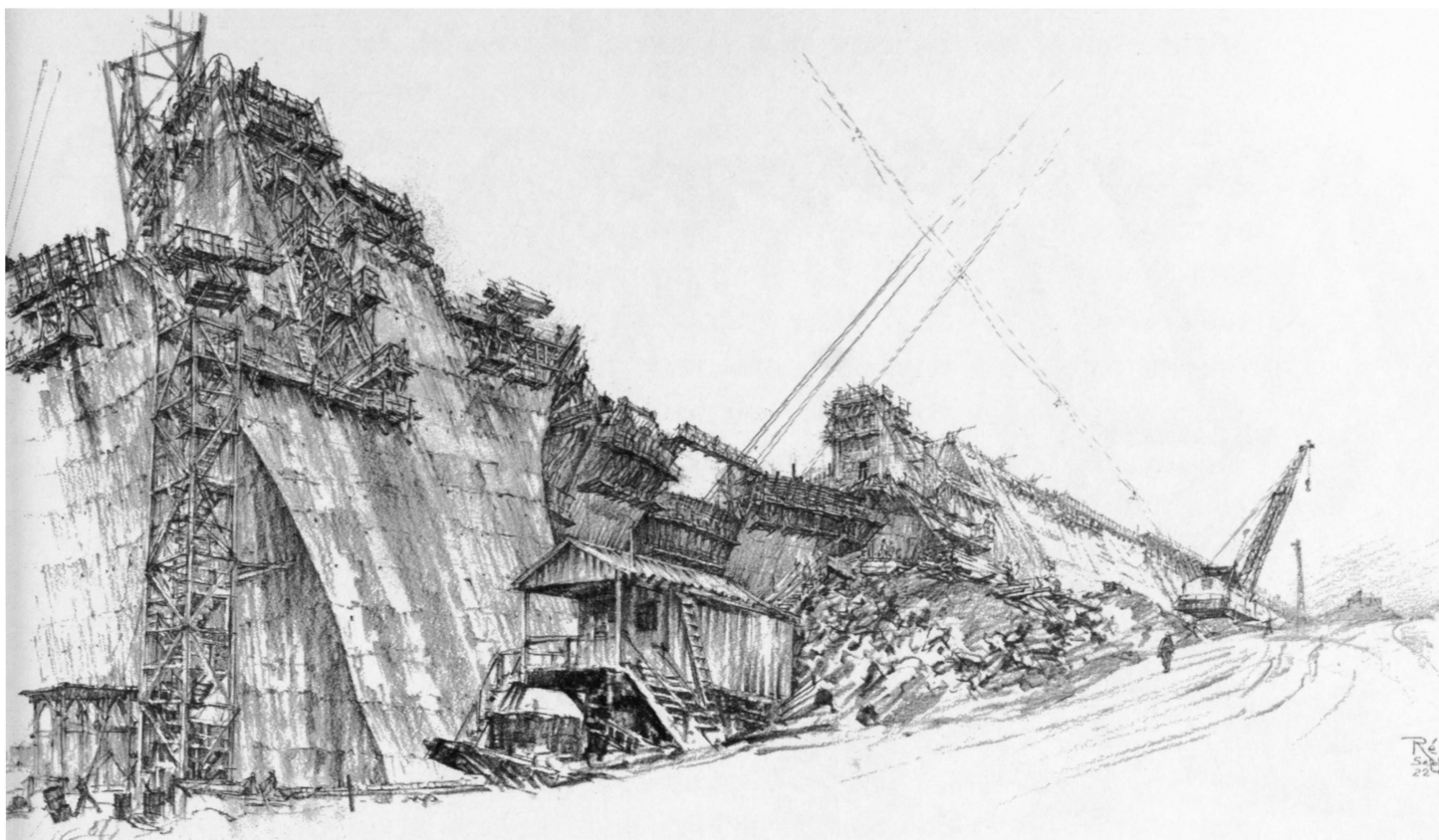


Two plumbers worked at the intricate grout piping system, fastening two pipes together with a short piece of hose and two clamps like those used on an automobile radiator hose. Carpenters were making last-minute adjustments in the formwork around the waterstops. They were checking against a blueprint just like men in a cigarette commercial. But there was no advertising man from Madison Avenue here. These men were real, grimy and tanned from the sun and the cold bush-country winds. It was summer, but many men wore long underwear. At night up on the dam it did not always feel like summer, especially if it was raining and the wind was blowing.

The weather at Manic 5 was like that a lot. It reminded me of a northern version of tropical weather: very changeable. On a beautiful cloudless June day, temperature around 65, angry-looking clouds would appear quite suddenly and within an hour a rainstorm would come. The men on the dam

By the fall of 1966 the elevators have become the only practical route to the top of the dam, now taller than a 40-story skyscraper near its center. The ride up is not half as frightening as leaving the car at the top.



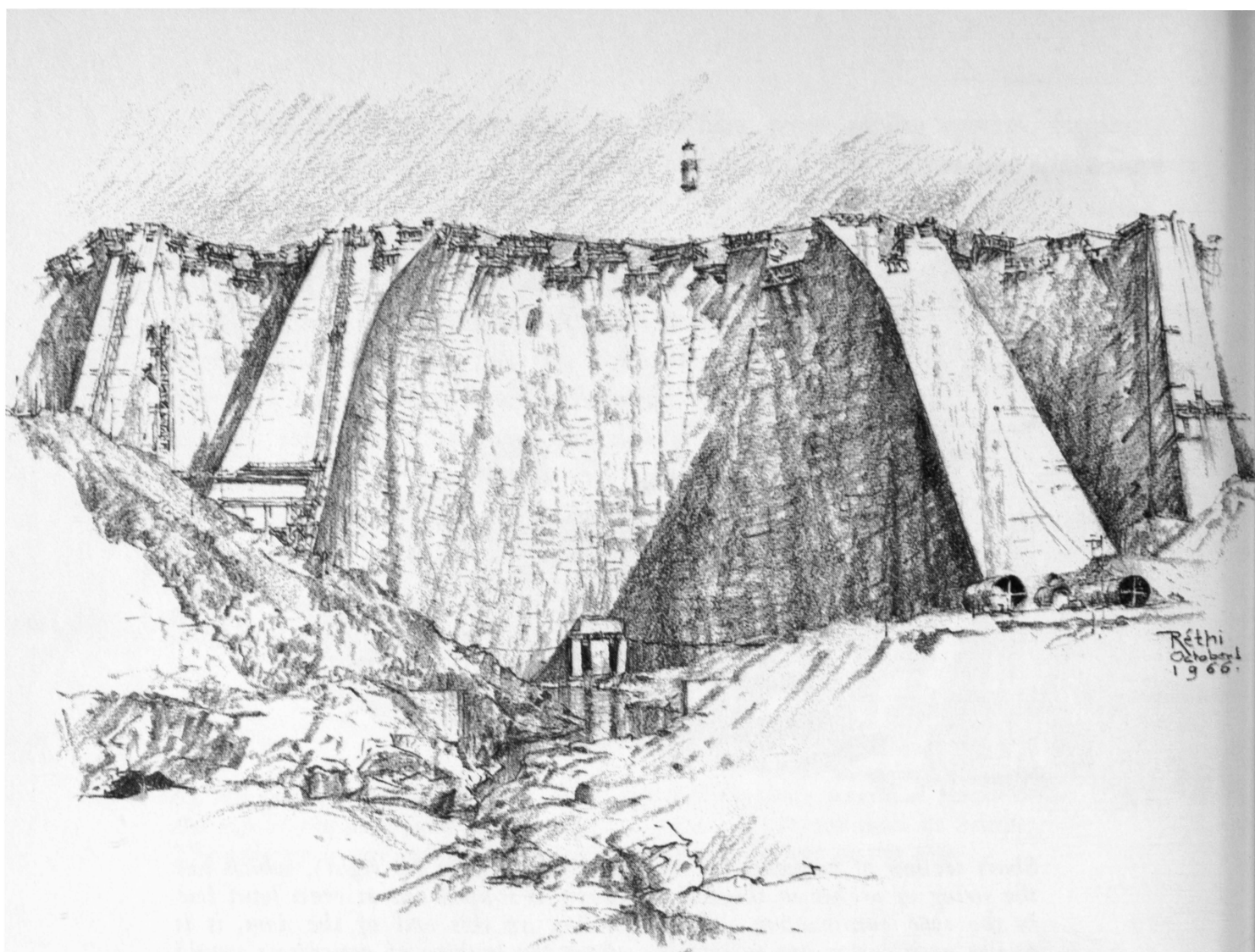


Short section of conventional concrete gravity dam (at right), which ties the string of arches to the east abutment, is topped out at crest level late in the 1966 construction season. Standing on this end of the dam, it is finally possible for one to imagine where the beehive of concreters would stop.

donned their slickers, which most kept rolled up, sometimes tied to their belts. Work continued. The buckets kept coming, the vibrators kept whining. The only effect a heavy rain would have might be that the batch plant operator would have to lower the water content of the concrete. His sand and coarse aggregate would be coming in wetter. The concrete in the lift would be getting wet. So he simply reduced the amount of water per cubic yard while the mixers kept on churning out concrete.

Concrete leaving Manic's batch plant could be sent to three different loading hoppers. One belt-conveyor system took concrete to a loading hopper that serviced the cableway buckets. Here a fleet of three semitrailer trucks ran continuously back and forth between the hopper and the bucket-loading dock, a kind of concrete shelf built into the steep slope between the dam and the batch plant.

These specially designed trailer trucks were called "silobuses." Instead of a conventional trailer, theirs was really a square hopper with an emptying chute on the left side. The 8-cubic-yard hopper's chute extended beyond the side of the trailer's chassis and had an air-operated gate. When a silobus



By October of 1966 the main arch is beginning to curve inward and seems deceptively close to completion. But the last bucket of concrete is still two years away.

arrived at the dock, usually at least one cableway bucket would be hanging in wait.

A radio dispatcher had guided the bucket into position—either hanging with its lip even with the deck of the loading dock or resting on a timber platform designed to keep it at this level. The silobus would pull up until its chute overhung the bucket. Then a workman plugged an air hose and an electric cable into the back of the trailer. The air line was to operate the hopper's gate, the power cable to operate a vibrator on the chute, used only if the stiff mix did not dump easily into the bucket.

Once the bucket was loaded, the radioman sent it on its way, off to a lift somewhere on the dam that neither he nor the cableway operator could see. The silobus then jackknifed around and headed back to the loading hopper, as another loaded one pulled up to the dock. A quick look upward would find another highline bucket gently easing down from the sky. The

never-ending aerial delivery of concrete was nothing but a monotonous routine from this vantage point.

But there were two other loading points for concrete. One immediately next to the silobus loading hopper was used to fill Dumpcretes, the special rear-dumping trucks used to haul concrete anywhere on the project where the cableways could not reach. Sometimes these big 18-ton trucks, with their scoop-shaped bodies that could hold 8 cubic yards of concrete, would rumble down the hill from the batch plant, cross the river on one of the two bridges, then whine up the west side of the valley to bring concrete to the gate-leg crane working the extreme west end of the dam.

Other Dumpcretes loading at the third hopper, up the slope from the batch plant, hauled concrete to the big revolving gantry crane working the gravity section at the west end of the dam. This crane had a 150-foot-long boom that raised concrete in 4-cubic-yard buckets. Once this crane had a bucket on the hook, it not only could revolve 360 degrees, but its supporting gantry, mounted on rails, could move horizontally along a trestle.

While most of this activity was directly related to the dam, it was also obvious, if one stood around these concrete loading hoppers for a while, that there was more going on at Manic 5 than dam concreting. There was almost always a big yellow Dumpcrete pulling up to one of the hoppers. Hydro-Quebec's big trucks were all painted orange, and the yellow ones seemed out of place when they appeared on the job.

These trucks belonged to Janin Construction Company, one of the few private contractors to work at Manic 5. Janin had been there in the early years driving the diversion tunnels. Now it was back, having won the contract for excavating two huge power tunnels and the eight penstocks leading to the powerhouse to be built downstream from the dam on the east bank.

XIV Janin's Dumpcretes were always fascinating to watch because they inevitably would leave the batch plant with a load of concrete and then mysteriously disappear into the side of the mountain through a tunnel. Janin specialized in underground work at Manic 5, one of the few areas where Hydro-Quebec's construction forces called on outside contractors. It was not as obvious, but there was a lot going on under the east bank of the Manicouagan River, all just as important as the construction of the dam itself. A hydroelectric dam would be of no use without a power plant, and the water would come to the power plant directly through this mountain.

The early design proposals for Manic 5 called for a powerhouse to be built directly downstream from the main arch—in fact, it was to have been located right at the dam's base, within the main buttresses. But a turn of events in faraway Montreal had a profound effect on the design of the project.

In the early 1960s the government of Quebec, under the leadership of Premier Jean Lesage, decided to bring in a second consulting engineering firm to the Manicouagan project. Asselin, Benôit, Boucher, Ducharme, Lapointe, a Montreal firm with a name that fairly well demands abbreviation, was charged with the design and construction supervision of Manic 5's power-generating facilities. One of ABBDL's first major recommendations was that the powerhouse be located farther downstream from the dam on the left bank. This would avoid the complications of running penstocks through the main arch to convey water to the turbines, ABBDL reasoned. Also, dam construction could proceed unimpeded by work on the power complex. There were other reasons for the design change, some of which involved cases of pure engineering opinion. Years later, engineers from Surveyer, Nenniger & Chênevert, consultants on the dam, would still debate the case for their integrated powerhouse.

At any rate, Hydro-Quebec's engineers decided to go with ABBDL's design, and work began on the underground complex of tunnels that would prove to be a spectacular construction job in its own right. Just east of the

dam's left abutment two big tunnels, 36-foot-high horseshoe-shaped bores, would pierce the mountainside. Once the tunnels were into the solid rock about 100 feet, they would plunge downward at a 30-degree angle for about 600 feet. At the foot of this major incline, the tunnels would level off maintaining only a slight gradient of 5 per cent for another 2200 feet.

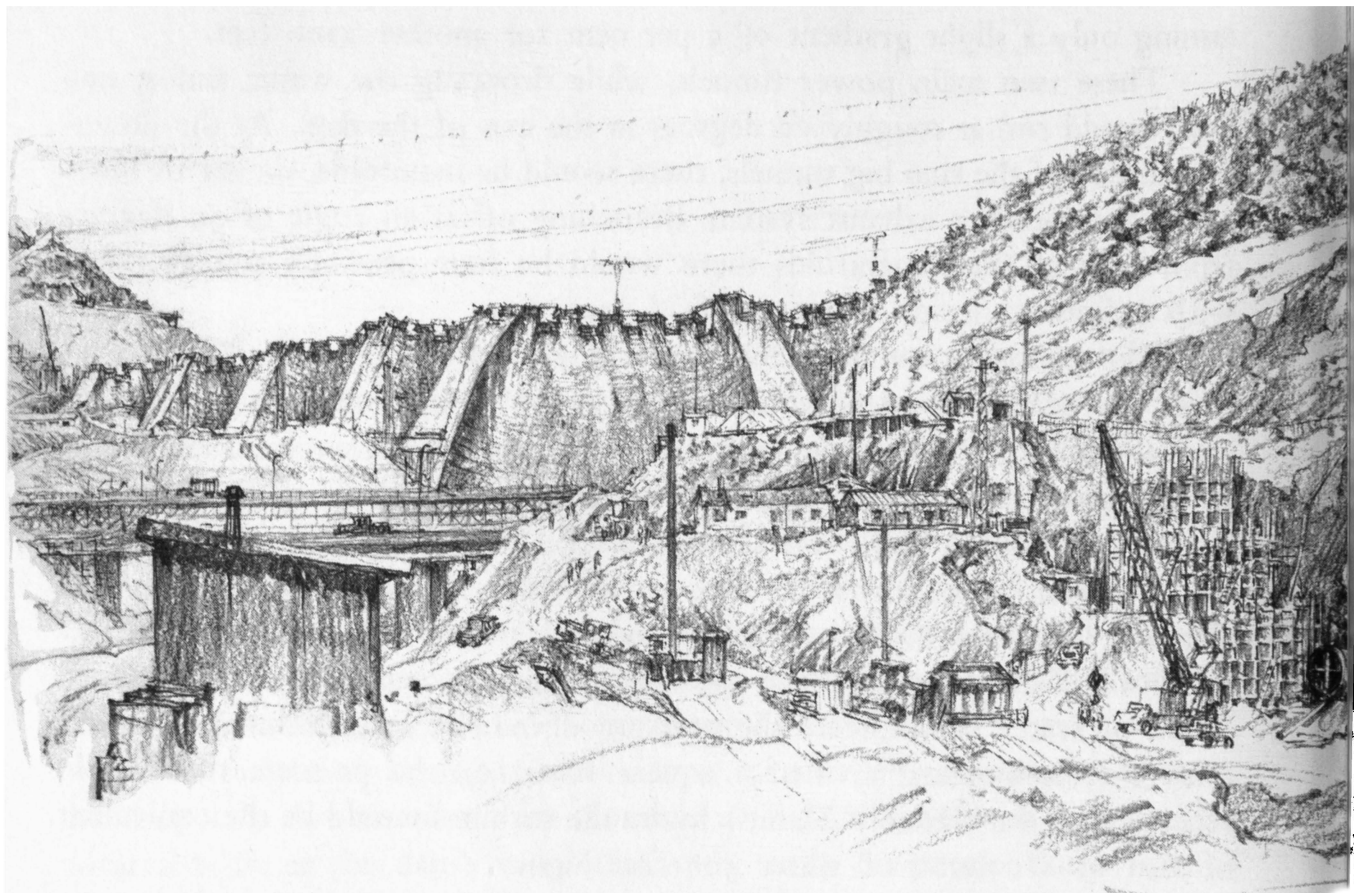
These two main power tunnels, while dropping the water almost 400 feet, would run at roughly 60 degrees to the axis of the dam. At the downstream end of the two big tunnels, there would be manifolds, similar to those on an automobile's exhaust system. Branching off at an angle of 42 degrees from each of these manifolds there would be four penstock tunnels, each with a finished inside diameter of 16 feet.

The penstock tunnels' length would vary from 627 feet to 858 feet. Their downstream outlets would emerge from the mountainside in a perfect row at the back wall of a huge excavation blasted from the river bank about $\frac{1}{2}$ mile downstream from the dam. Maximum water level in the reservoir would be elevation 1180 feet above sea level. The centerline of these penstock tunnels' outlet portals would be at elevation 674 feet. The mathematical difference between these two figures, 506 feet, would be the so-called operating head of Manic 5's power turbines. Hydraulic engineers use the term "head of water" to indicate the pressure developed by a column of water with a cross-sectional area of 1 square foot, i.e., the pressure that would react against the blades of Manic's hydraulic turbines would be the equivalent of that of a column of water 506 feet high.

One other "minor" detail of the underground excavation work was the surge shafts. These are vertical shafts that run from the tunnel's downstream ends to the surface, which at Manic 5 was 385 feet above the tunnel manifolds. The purpose of the surge shaft in a hydroelectric plant is probably best explained by comparing the huge system of tunnels and penstock tubes to the plumbing system in a residential home.

If the water piping system in a house is not properly designed (and many are not) air can become trapped in the pipes. When a faucet is turned off suddenly (particularly the very rapid, positive-acting valves like those in a washing machine), a phenomenon occurs called "water hammer." The air and water in the pipes begin bouncing around, surging back and forth, causing the pipes to vibrate and hammer. Water hammer is not a desirable situation in a domestic plumbing system, but when the problem is projected into a system such as that at Manic 5, where the "pipe" is 36 feet in diameter (the small ones, 16 feet in diameter), the consequence becomes something more than annoying. Serious water hammer can cause tunnels to collapse, even when lined with steel and concrete. And so the surge shaft.

In the unlikely event that Manic 5's powerhouse were to be completely shut down—all eight units stopped by shutting off the flow of water at



Manic 5's powerhouse, to be located about half a mile downstream from the dam on the east bank, is mostly a big hole in the ground in 1966. But a row of eight tunnel portals for the penstocks reveal that there is considerable activity within the mountain.

the downstream end of the system—there would be a tremendous surge of pressure. Water hammer could develop that would threaten the entire system. The surge shafts are, in effect, mammoth pressure relief valves. Should there be a shutdown, the water rushing through the tunnel would surge up the shaft.

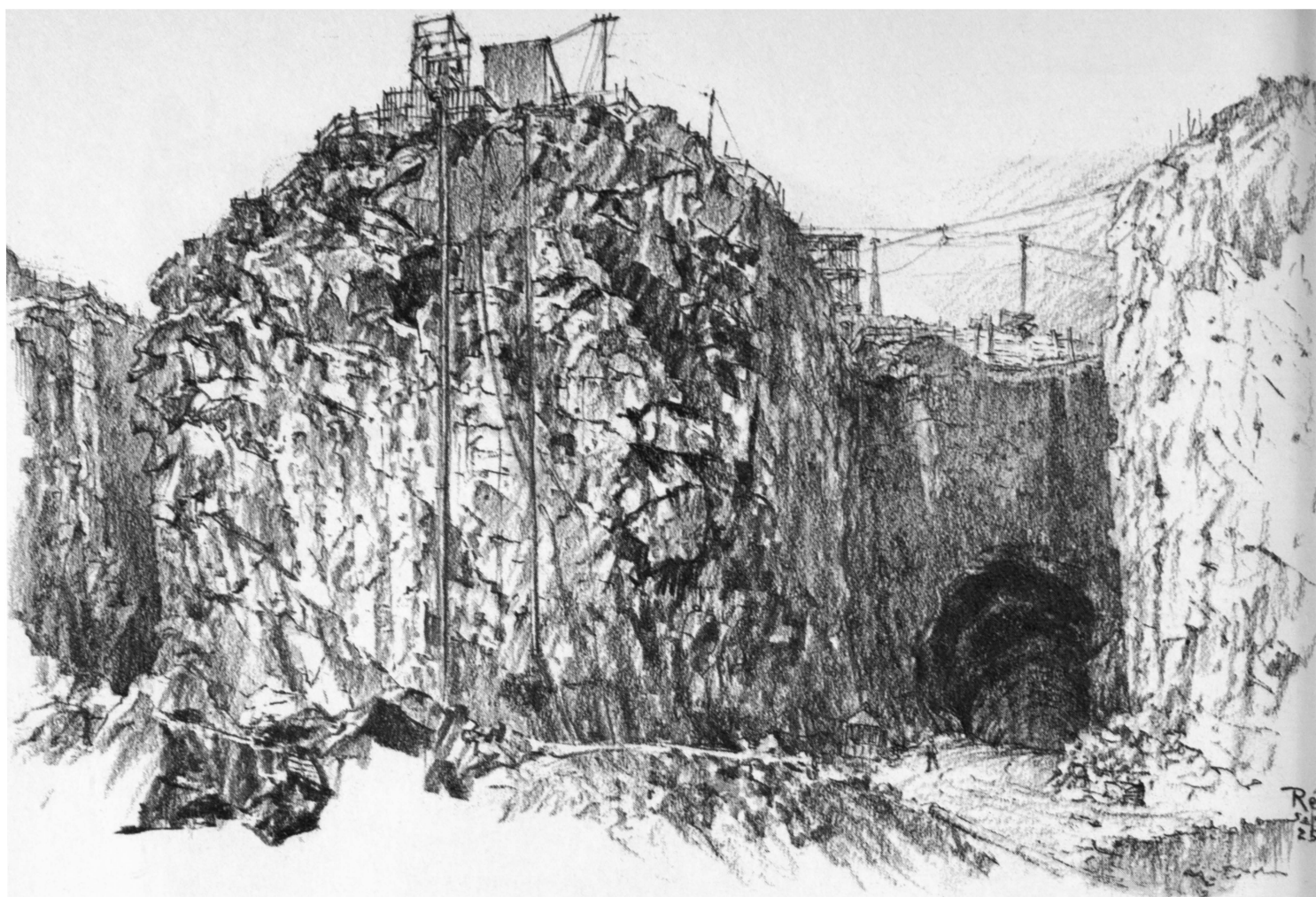
Theoretically, it would surge at least as high as the level of the water in the reservoir, on the principle that water seeks its own level. Because of this eventuality, the surge shafts at Manic had to be topped with surge tanks. The vertical rock shafts emerged from the mountainside at elevation 1075, 105 feet lower than the ultimate maximum level of the reservoir, elevation 1180. If our theoretical shutdown were to occur, water would



surge up the shafts and spill out, running down the hillside right into the powerhouse.

So the shafts had to have tanks built above them, extending up at least as high as the reservoir's water level. The final design of these tanks called for 80-foot-diameter tanks 175 feet high. This leaves 70 feet of freeboard for any sloshing around that might take place—all in all, an extremely expensive safety valve to guard against something that probably will never happen. Few hydro plants ever have occasion to shut down generating units en masse, but the engineers must plan for the worst.

During the 1965 season Hydro-Quebec crews began excavating the more than 400,000 cubic yards of rock and overburden—the loose dirt and



Power tunnels, a pair of 36-foot-high tubes, begin upstream of dam's axis (portal of west bore pictured here) and plunge steeply downhill 600 feet. At foot of incline they run for nearly half a mile before splitting into smaller penstock tunnels that emerge at powerhouse.

rock covering the bedrock—for the powerhouse. Before blasters could get at the 250,000 cubic yards of rock that had to be removed, bulldozers, big power shovels, and trucks had to haul away 186,000 cubic yards of overburden. This work had to be at least partially completed before Janin, working under an \$8-million contract, could begin boring into the mountain.

Janin had mined in the rock of Manicouagan gorge a few years before, driving the two big diversion tunnels, but then they were on the east bank. This underground power complex was on the other side of the river and, although the borings promised good rock, the Janin firm was an experienced tunneler and its engineers knew how conditions could change, sometimes even in the same tunnel within a few hundred yards. Would the power penstocks and tunnels be as good as the diversion tunnels turned out to be? Tunnelers never know until they get “in the hole,” to use construction vernacular.

Janin's hard-rock men started with penstocks Number 4 and 6, driving upstream, one might say. They had to drive these two relatively small tunnels,

roughly 20 feet in diameter, in order to gain access to the two big tunnels. Using a drill jumbo built around a big Euclid dump truck, the drillers worked these two tunnels full face, rather than the top-heading and bottom-bench method used for larger bores.

Once the tunnelers had blasted their way to the larger manifold sections, they ramped the tunnel upward to begin the top headings of the main power tunnels. The driving of the two big tunnels, which would be about 40 feet high, roughly horseshoe-shaped in section, turned out to be relatively routine.

At least, Mario Laudadio, Janin's youthful project engineer (twenty-eight years old when I first met him) was rather casual about it: "Standard ladder drilling, top heading, and bench method." But when one hopped into his little yellow pickup truck and drove right into one of the penstock tunnels, the job did not look at all routine. Laudadio wheeled through the tunnel as though out for a Sunday ride, his headlights piercing the dimly lit, rough-hewn bore.

The real scope of the underground work hit when one emerged from the penstock tunnel and turned left into the main tunnel. In the early months, one really saw only half a tunnel, an arched roof section about 18 feet high. The drill jumbo, with its various platforms for the drill rigs, looked like what it was—the dirty, banged-up work horse of the tunnel-driving operation. The jumbo's platforms carried twenty-five air-operated drilling machines, several on the uppermost platform, eight or nine each on the middle and lower decks.

Each drill was mounted on ladder-like devices, which made it possible for the driller to set up the drill for a particular hole in the pattern and then, once he had started the drill into the rock, to leave the machine unattended for a period of time. This meant that one operator could attend at least two drills (a development that has not been particularly well received by labor unions, especially in the United States).

In fact, Janin's typical jumbo crew consisted of one shift boss, four men called "leaders" and thirteen drillers. For each so-called round, or cycle, the jumbo crew drilled 140 holes 16 feet deep. These were then charged with dynamite (sticks $1\frac{1}{8} \times 8$ inches), the jumbo was driven away from the heading, and the shot detonated, or "fired," as the tunnelers say. Laudadio's boss, Janin project manager Paul Poulin, figured that in Manic 5's power tunnels they had averaged about 12 feet per round with two 10-hour shifts averaging about four rounds each day. This came to about 300 feet of tunnel a week in the hard granite-gneiss, which both Poulin and Laudadio agreed was good sound rock all the way, an important factor to hard-rock men.

This is one of the paradoxes of tunneling. The harder and more solid the rock, the easier the tunneling goes. Bad rock, blocky and full of seams,

changing formations with faults and their attendant regions of poor rock that often are water-bearing—all this is bad news for the tunneler. The toughest tunneling of all is said to be what is called “soft-ground tunneling” (though some hard-rock men might disagree). Although this may be oversimplifying, a fairly safe rule is that the easier the material is to dig—for example, soft clay or silt—the more difficult it is to tunnel through. The main reason for this, of course, is that the easily dug material is usually not self-supporting. A tunnel through the sloppy muck of a riverbed is far more difficult to build than those Laudadio was punching through the hard gneiss rock at Manic 5. The Manic 5 tunnels, however, were no Sunday-school picnic.

After each shot Laudadio’s mucking crews moved in with two crawler

One place where work can continue even in the dead of winter is deep inside the mountain. Here workers prepare huge steel form used to place concrete lining in power tunnels. Vertical surge shaft nearly 40 feet in diameter rises to surface at top of picture.



tractors, each equipped with side-dumping front-end loaders. These loaders mucked out the broken rock, loading 20-ton rear dumps, which jockeyed in the narrow quarters, hauling the muck out of the penstock tunnels and up out of the powerhouse excavations to various dumping areas in and around the camp. This rock could have been used as aggregate for the concrete plant but was not, mainly because of the steep, long haul up the mountain to the primary crusher. The haul from the quarry was far shorter, faster and downhill.

Once the miners had completed the arch sections of the two tunnels, one 2290 feet long, the other 2128 feet, they then began excavating the so-called bench, the lower half of the tunnel. This two-stage method is used in large tunnels mainly because the lower half can be more easily drilled for blasting. Instead of having to drill horizontal holes into the face, working from precarious platforms, the drillers can place crawler, or wheel-mounted, rigs on the floor of the top heading to drill vertical holes for the bench cut.

Unlike Manic 5's big diversion tunnels, these power tunnels had to be lined with concrete. Whereas diversion tunnels are strictly by-passes for the river and temporary at that, power tunnels are part of a delicate, however large, hydraulic system. Their flow capacity is carefully calculated so they will supply precisely the proper number of cubic feet per second to each of the penstocks leading to the big turbines.

The lining of concrete creates a tunnel of uniform size with smooth walls to facilitate the flow of the rushing water. It also prevents the water from eroding the rock, which could trigger a major rock fall that would block the tunnel. In fact, even small rocks breaking loose from the walls of an unlined tunnel can damage the blades of the powerhouse turbines.

The design of pressure tunnels such as those at Manic 5 is far more complex than merely blasting a hole through the mountain and lining it with concrete. The pressure of the water in such a tunnel is so great that designers must take into account the ability of the overlying rock to withstand the tremendous forces. For example, on the blueprints for Manic 5's power tunnels there was what appeared to be a line with arrows on each end as though to give the distance between the top of the tunnel and the rock line at the surface. But no dimension was shown, only the phrase: "Minimum —50% of local head."

What this meant was that at any given point, the tunnel had to be below the surface a distance equal to at least half the head—the hydraulic head expressed in feet—at that point in the tunnel. Put another way, if the hydraulic head exerted in the tunnel at a given location was to be 400 feet, the rock cover above the tunnel had to be at least 200 feet thick.

This helps to explain another aspect of the elaborate underground com-

plex. At the downstream end of the system, where the penstocks peel off one by one from the main tunnel to emerge from the mountainside at the powerhouse, the tunnels are not only concrete lined, but also have a steel liner within the concrete. This steel lining, which begins in the penstock tunnels soon after these 16-foot-diameter tubes leave the manifold, varies from $\frac{1}{2}$ inch thick at the upstream end to 2 inches at the downstream end where the penstocks enter the powerhouse.

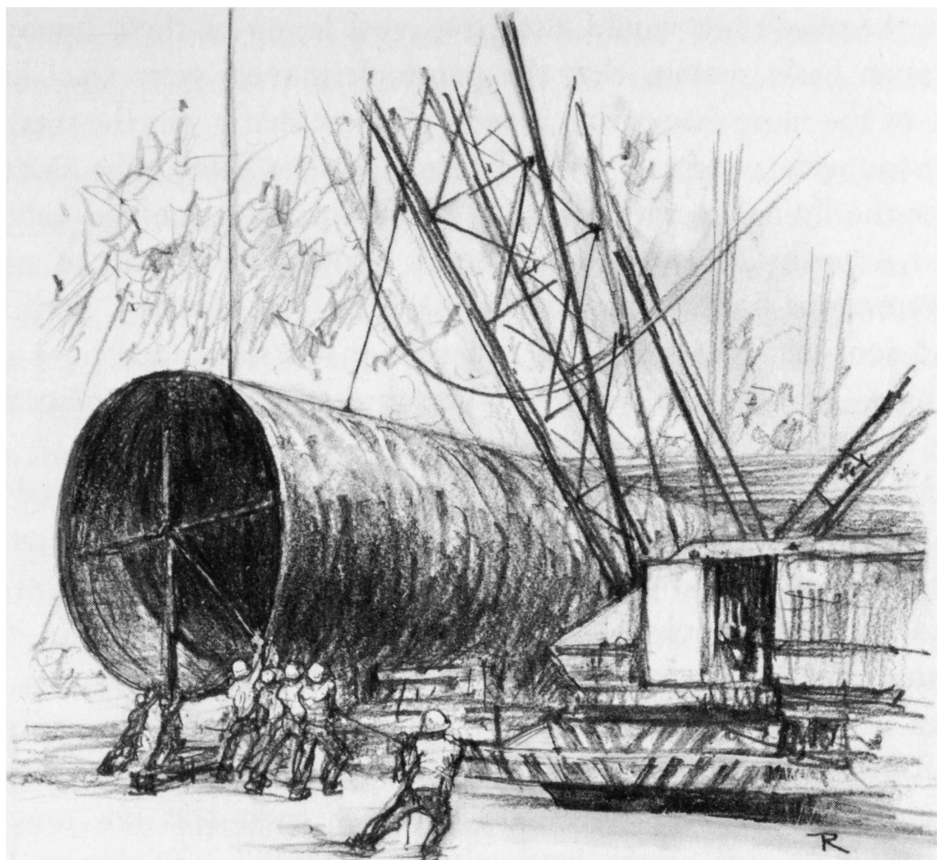
The reason for the steel lining in the penstocks is that there was not enough rock cover because of the slope of the mountain. In other words, as the underground tube comes closer and closer to emerging from the mountainside, it must be made stronger. This is the point where the pressure of the water will be greatest, but where the tunnel—really the surrounding rock—is less able to absorb some of the force.

So the steel tube, by the time it leaves the tunnel and enters the powerhouse, has walls 2 inches thick. The penstock is designed here the same as if it were free-standing, as in fact some hydroelectric penstocks are. This steel lining also protects the concrete tunnel lining from what engineers call “cavitation,” a kind of erosion of the concrete caused by the rushing waters.

Laudadio’s crews began installing the concrete lining, a relatively simple process involving a huge wheel-mounted steel form that creates the inner configuration of the finished tunnel as concrete is pumped behind it. These huge forms for tunnel lining are what the tunnelers call “collapsible,” a misnomer in a way. After the concrete has set, what they do is fold inward slightly on the sides and the arched roof part lowers slightly. Then the entire assembly can roll forward to line another 40-foot section. This operation was the destination of the stream of yellow Dumpcretes I had first noticed up at the concrete plant. They drove into the bowels of the mountain where Janin’s men were finishing the two big tunnels except for their curved floor sections called the “tunnel invert.”

This was not concreted because the tunnels that would one day convey water were now being used as road tunnels. While Janin worked on the lining during the winter and summer of 1966, there was a lot of action in other parts of the subterranean network. Much as Hydro-Quebec had contracted out the underground work to Janin, the contractor had, in turn, subcontracted some of the more difficult areas of rock excavation to Evert Ross and Associates, a company from Val d’Or, Quebec, that specializes in mine shafts and other tricky aspects of the mining operations so common to the north country.

Evert Ross was brought in to mine the two inclined portions of the power tunnels and the two vertical surge shafts. The surge shafts were a relative breeze, according to Ross’s hard-rock men, but the inclines were



Workers strain on guide rope as crane positions one of the huge steel sections used to line the penstock tunnels. Trucks have hauled these prefabricated units up the long road from Baie Comeau on the St. Lawrence.

bad news. Miners began the vertical shafts by driving what is known as a “raise.” They drilled and blasted a 7×7-foot pilot shaft from the bottom upward. This sounds illogical to the uninitiated, but actually is faster and easier since the muck—the broken rock—does not have to be hauled up from the bottom of the deep narrow hole. Instead it falls downward when the blast occurs and is simply cleaned up at the foot of the shaft and hauled out one of the penstock tunnels.

Once Evert Ross had completed the pilot shafts, its crews could begin widening them. To do this—an operation miners call “slashing”—the men worked from a platform suspended from cables anchored at the surface 385 feet above the tunnel roofs. Their first step was to drill and shoot the shafts to a diameter of roughly 19 feet, working downward this time and shoving the muck down the shaft with each round.

When the shafts were slashed out to 19 feet, the miners reversed themselves and slashed from the bottom upward taking them out to their final 39-foot rough diameter. The top 100 feet of these shafts was widened out

to 40 feet because they would also have steel lining in these upper reaches for the same basic reasons that the penstock tunnels were steel lined.

One of the more fascinating aspects of these shafts was the method used to line them with concrete. Once Evert Ross had mined the shafts, Janin took over the lining operation, and it was done by a method called "slip-forming." As many times as I have seen it done, it never fails to amaze me. It is a continuous operation, wherein the form (at Manic 5, nothing more than a 36-foot-diameter steel shell 4 feet high) is suspended by a circle of jacking bars. These are raised at a given rate as concrete is placed behind the form in a non-stop operation.

At Manic 5 the surge-shaft slip form was of course reinforced by steel spokes which also served handily as a work platform for the concrete crews. The platform and form hung from sixteen long steel bars which were held by special hydraulic jacks and carefully controlled by a single hydraulic console that raised them evenly at a rate of about 1 inch every five minutes.

Janin brought a young technician up from Montreal specially to run this slip-forming operation. Ed Huslid was Norwegian and added, once again, to the international flavor of Manic 5. His French was not much better than mine, which was pretty ineffective, but Huslid was able to keep the surge shaft's concrete lining on schedule despite the language barrier. He was on call at all times, and more than once while we dawdled over a beer at the foremen's club, a French-speaking bartender would take a phone call, then tell the Norwegian there was trouble at the shaft.

One of the most common problems would be a malfunction of one of the sixteen jacks, 3-ton units fitted with two sets of special gripper claws, one set to hold while the jacks were retracted, the other to grip the rods when the jacks were raising. If one jack stops working, the other continues to lift and because of the gripper arrangement, will buckle the inactive rod. So Huslid had to act fast; the beer glasses left half full, we went up to the shaft one night.

The slip-forming process is continuous and cannot be stopped without jacking the form up above the green concrete. Otherwise, the form might become stuck to the concrete. In fact, on weekends, when the project did halt for a brief two shifts, the final phase of Huslid's week was to jack the form up after the concreters had gone for the night. But during the normal work week concreting was continuous. So if one jack broke down, it was replaced as work continued.

The night we arrived, we could see the bad jack immediately. Its long rod extended down into the shaft but not in a straight line like the others. After releasing the gripper devices, Huslid removed the faulty jack, quickly replacing it with a spare unit. Meanwhile, a Dumpcrete, standing near the shaft mouth in the darkness, was pouring concrete, a somewhat wet grit-

mix, down a chute that filled a small hoist bucket. This bucket also was to be our elevator, I learned, delivering us to the work platform hundreds of feet below.

As Huslid and I went down instead of a cubic yard and a half of concrete, the most impressive sight was the walls of the big shaft. Although slightly screened by chain-link fencing, rock-bolted to the walls to protect the workers from spalling rock, the granite-gneiss was a display to thrill a geologist's heart. Rock outcroppings on the earth's surface occasionally reveal beautiful stratifications and the tortured folding that has taken place eons ago. But the trip down into Manic 5's surge shafts prior to lining was fantastic. The blacks and whites of the metamorphic rock looked like the work of some giant impressionist artist, broad swirling strokes, an occasional diagonal stratum slashing across the granite, an ancient intrusion of molten igneous rock that had found its way into a seam or fault. It sounds silly, but Ed Huslid had taken me into a beautiful hole in the ground. It seemed a pity it would soon be covered by man's dreary concrete.

But soon our bucket elevator came to a stop and we climbed out onto the rough timber platform. About six men waited, dressed in the underground construction man's usual filthy garb, some with yellow slickers, the label JANIN across their backs. Around the perimeter of the platform was the top rim of the form, wet concrete being manhandled and vibrated into place. Our elevator returned from above, this time full of concrete. Workers used small, rubber-tired concrete buggies to take concrete from the platform center to the outer edge where it was placed so that it was relatively level all around.

Suddenly the platform shuddered slightly. Huslid smiled at the expression on my face. The jacks had just raised us an inch. We were slip-forming. "Our beer is getting warm," I reminded Huslid with an air of bravado which did not really conceal my true feelings. And we rode the empty bucket back to the surface. It was raining and a fog was rolling in over the dam which was about even with our mountainside perch. It seemed that with each passing year as the huge lake formed behind the dam, the fogs were getting worse and more frequent. Later, at the airport, I checked the weatherman. He agreed that the ever-broadening water surface, now backed upriver for about 75 miles, was indeed affecting the weather. He made no long-range forecasts, but did jokingly suggest: "By the time we're through here, maybe we'll permanently close down our own airport." As if this did not happen often enough now.

I was reminded of one of my first flights—in 1962—to Manicouagan. At Montreal I boarded one of Quebecair's graceful F-27s, a twin-engined turboprop plane with its wings high on the fuselage. The landing gear keeps the plane's belly only about 3 or 4 feet off the ground and I wondered

about the gravel landing strip at Manicouagan. After stops at Quebec City and Saguenay, the little Fairchild took off for Baie Comeau. The weather, which I later found to be normal, was going from bad to worse. Fog and rain persisted as we approached Baie Comeau. Would we be able to land, or worse, to where would we be diverted if Baie Comeau was socked in? But the young pilot put us down beautifully in the driving rain.

We ran through the rain to an old wooden terminal building crowded with an assortment of people. The men wore varied attire from rugged work clothes to business suits. Women and children were dressed casually. Milling around the terminal, they were like people in any air terminal during bad weather—apprehensive, impatient, and, all but the children, unhappy. Eventually a public address system boomed into the small main waiting room: “Quebecair Flight 291 for Manicouagan and Gagnon now loading.” And we plunged out into the driving rain for the next leg. If this was Baie Comeau, I was thinking, what must Manic 5 be like?

That night I was not about to find out. About a half hour out of Baie Comeau the stewardess told everybody (in French) that the strip at Manicouagan was closed because of the weather. She then stopped by my seat and said in English: “We cannot land.”—Never? I thought—“We go to Gagnon.” She then distributed Lifesaver candies (an ominous brand for airlines to use) as we flew another 100 miles beyond Manic 5 to the mining town of Gagnon. After waiting around about an hour, hoping Manic 5’s weather would relent, we finally gave up, reboarded, and returned to Baie Comeau to spend the night.

The next night the F-27 touched down at Manic 5 so gently that I couldn’t feel it at all—something I learned is typical of a gravel runway. We taxied back to the terminal building, a far more attractive building than Baie Comeau’s terminal, though even smaller. Inside the terminal all was sparkling clean and freshly painted. Wooden benches stood in the middle of the waiting room, a small office in one corner was Quebecair’s counter and the only one. A brown-uniformed Hydro-Quebec policeman occupied another tiny office and checked everyone’s identification as he entered the terminal. Further exploring revealed Manicouagan’s weather bureau, tucked in some small rear offices of the building.

Not only was there a “Manicouagan” and a “Manicouagan weather bureau,” but, I was soon to find, a lot more. After a brief, high-speed ride in a pickup truck down a winding, ever-descending gravel road, the project came into view. We emerged from the darkness of the airport road into a valley of light. I had expected more than tents, but nothing like this. Spread out along the river’s right bank were what appeared to be hundreds of buildings. The lighted windows and street lights extended downstream as far as I could see. But the most exciting part of this nighttime panorama was

to my left. Like a string of mammoth Christmas lights, the highline of mercury-vapor lamps seemed suspended in space, flooding the gorge with light. "You can read a newspaper on the ground," my driver boasted in heavily accented English.

Lights blazed all over the slope across the river, where the concrete batch plant towered on its precarious perch. After a hearty meal in the big cafeteria, I was ushered to my quarters, a big house-trailer placed high on the west bank and providing a spectacular view of the entire project. My accommodations were fit for a king—hot and cold running water, a complete kitchen, electric heat and lights, three comfortable bedrooms. All the comforts of home, even a liquor cabinet. Roughing it in the bush was not as bad as I had expected. Sipping good Canadian whisky in what must be the best hotel in town, I relaxed for my first night at Manic 5.

XV Three years later I stood with Ed Huslid and surveyed the mid-night panorama again. A lot had changed, but the most pronounced difference was the way the dam now dominated the landscape. The concrete batch plant did not tower anymore: the dam loomed over everything. Most of the vantage points around the project where we used to go to overlook the whole job were overshadowed by the massive concrete structure. One of the best views in town now was from the top of the dam itself.

Back at the foremen's club, Huslid and I met Bernie Williams, chief engineer for Evert Ross and Associates. A burly, classic hard-rock man, Williams said: "If you think the surge shafts are something, you ought to see our damned inclines. Those guys used 30-degree slopes so they'd be easy to line with concrete. But a 30-degree incline is one hell of a thing to mine. Damn," he said, "we had to mine those sections in seven separate stages." The Ross crews began each inclined section at the bottom, driving a 7-foot-high, 15-foot-wide pilot bore. They left the muck in place, an old miner's trick which gave the drillers a rubble platform to stand on as they slashed back down the incline after the pilots had been holed through.

This downhill slashing was a two-part affair. While drilling and shooting a 3-foot slash off the roof of the pilot bores, Ross drilled 10-foot-deep holes in the side walls at about a 25-degree angle to the axis of the tunnels. These holes were not loaded, but plugged with wooden blocks to await completion of the side-wall drilling when the muck had been removed from the pilot bore.

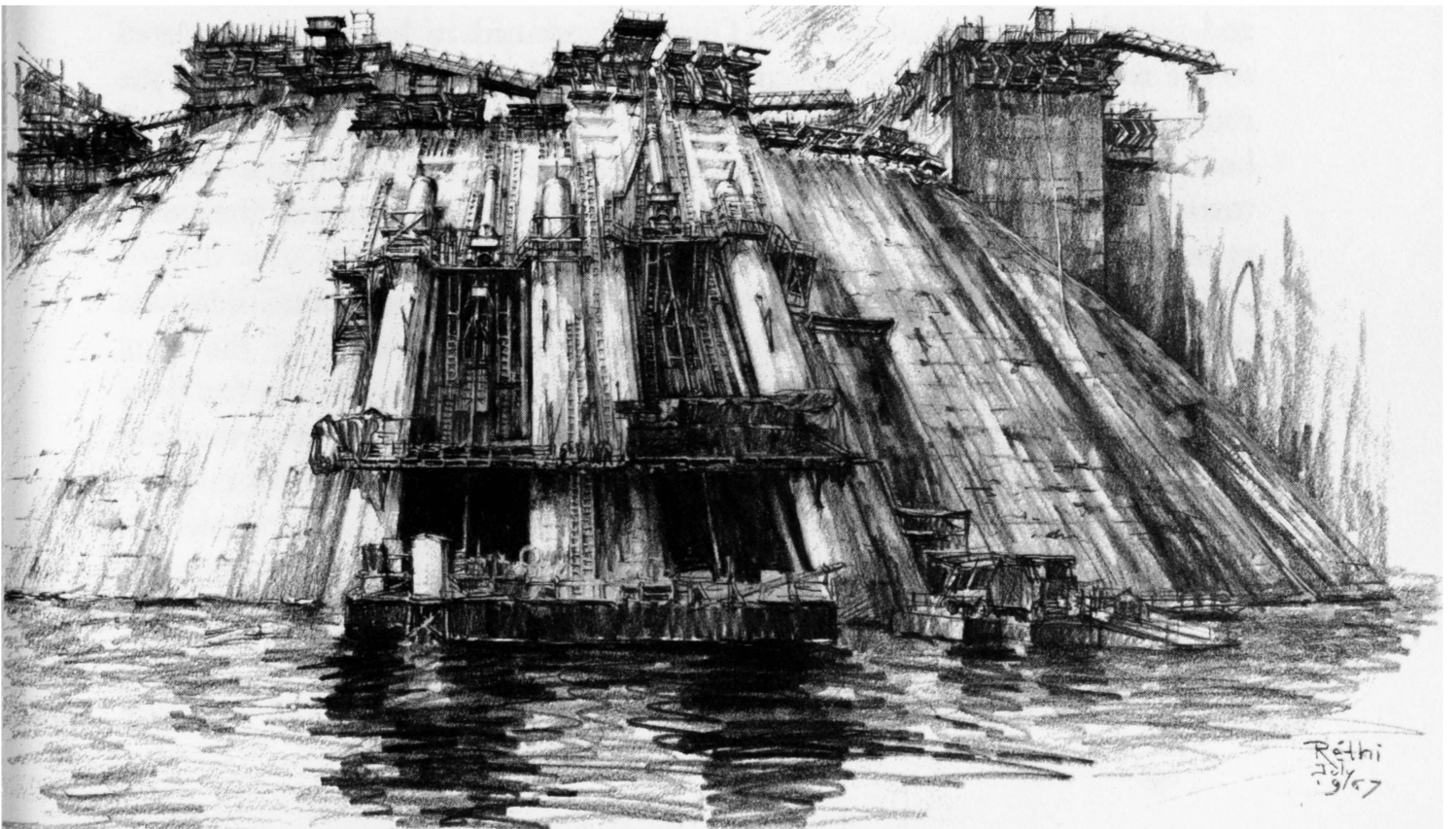
Next, using a job-built jumbo, a kind of rubber-tired wagon with tilted platforms so drillers could stand upright, the miners began at the bottom, drilling and shooting yet another slash, this time a 10-foot cut off the back or the roof of the tunnel. A crawler tractor began the tedious mucking operation by pushing the material down the inclines where it was loaded into trucks at the bottom. (This was the part that annoyed Bernie Williams, since the slope was too gentle, and the muck would not slide down to the bottom as it would in a steeper incline.)

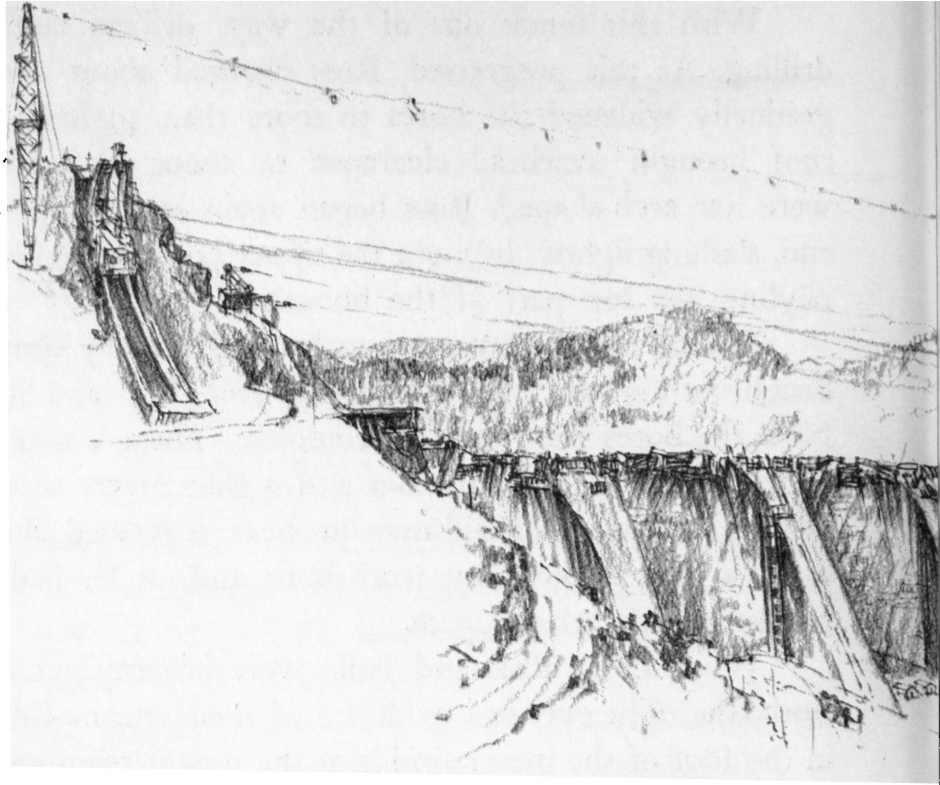
With this muck out of the way, drillers could finish the side-wall drilling. As this progressed, Ross charged about 200 holes at a time and gradually widened the bores to more than 30 feet. The deep slash in the roof brought overhead clearance to about 20 feet, but still the tunnels were not arch-shaped. Ross began again at the top with its wagon jumbo and, slashing lightly, brought the upper portion of the tunnel out to the final payline, the top part of the horseshoe.

Taking out the bottom bench was relatively simple. First a rectangular bench section was taken, about 16 feet deep and just over 30 feet wide. Now the bores were close to complete. There was only a kind of curb left on each side near the bottom and a thin invert section to be slashed out. But, as Williams had said over his beer, it seemed like one hell of a way to build a tunnel. But they were built and, as he had predicted, lined with concrete with relative ease.

While Evert Ross and Janin were blasting out this underground labyrinth, the only outward evidence of their accomplishments was eight holes in the foot of the mountainside at the downstream end and two rather large openings at the upstream end of the system. Although the dam dominated the project completely by the summer of 1967, a drive around the winding

Upstream face of the central arch, mostly submerged by 1967, still carries four big air vents and the control mechanisms for the upstream gates of the low-level outlets, hundreds of feet below the reservoir's waters.





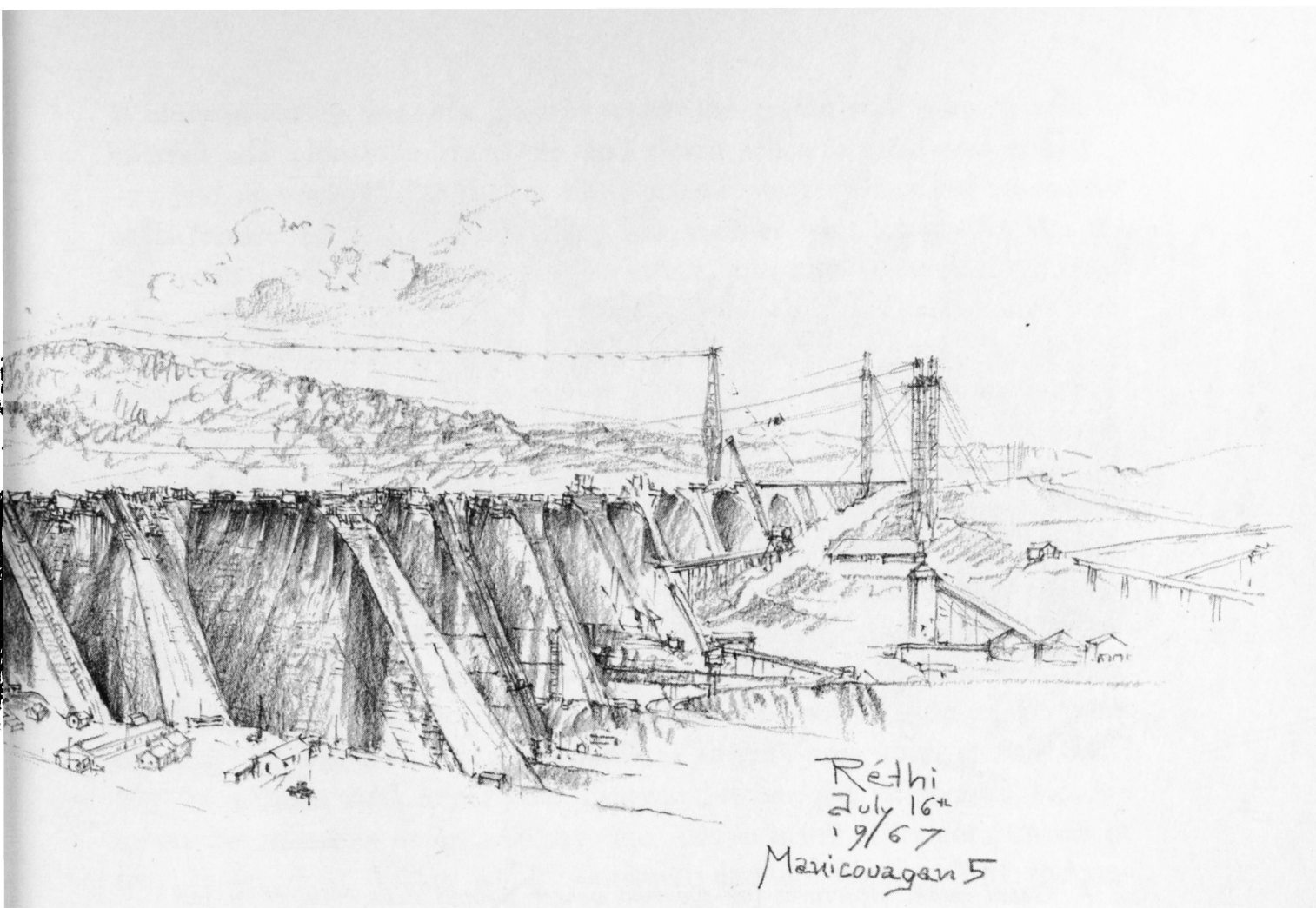
Over-all view from high ground on the west bank reveals the extreme east end of the dam topped out. The cableway highlines now are barely clearing the ever-rising central portions as arch after arch gets nearer to closure.

network of roads revealed several spectacular side projects. One of these was the intake structure for the two power tunnels.

The upstream portals of the power tunnels were to the east of the dam and slightly upstream of its axis. The work seemed to be almost unrelated to the rest of the project, tucked off in a big excavation blasted out of the rock of the left abutment. When the pickup truck drove down into the hole and one looked up, there was a sudden realization that these intakes, towering 150 feet high, were indeed a major bit of construction in their own right.

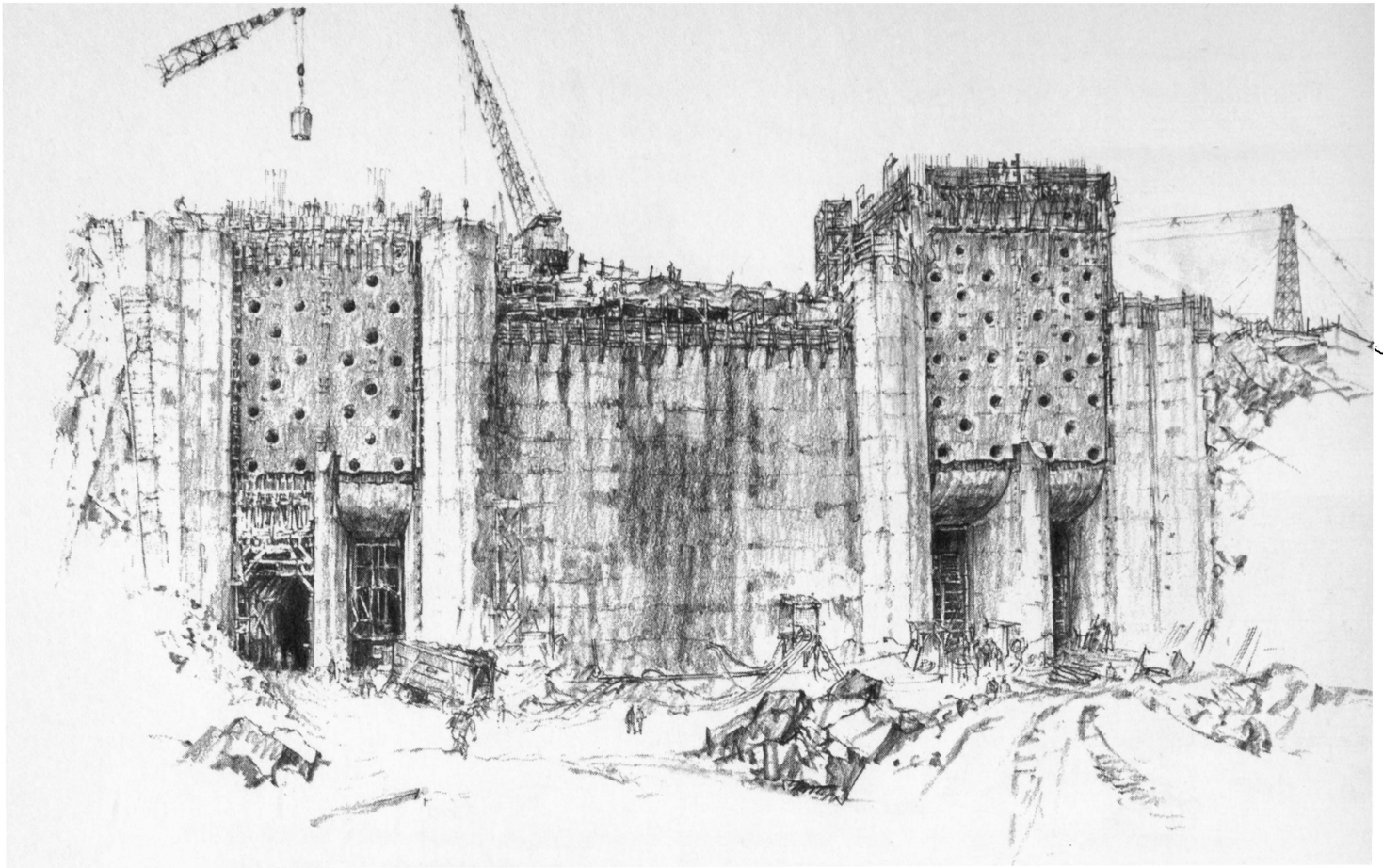
Our truck, parked on the floor of the big cut in the mountainside, was theoretically in deep water. Although we were out of sight of the dam, ABBDL resident engineer Jean Saindon reminded me that the sills for these intake gates were 130 feet below maximum water level in the reservoir, 150 feet below the crest of the dam. "I think these intakes are possibly the deepest in North America," Saindon told me. The reason for the tunnel intakes being placed so far below the dam's crest was to permit the powerhouse to operate even when the reservoir is as low as elevation 1115, a healthy 65 feet below maximum pool.

Designers, working with relatively skimpy long-range precipitation and



river-flow records, typical of remote areas, had to allow for drought periods up to four or five years long and, of course, runoff dribbles away to almost nothing each winter when the big freeze comes. So they placed the powerhouse intakes considerably lower than the design maximum water level. Although in July of 1967 Manic 5's reservoir was rising at the rate of about 8 inches a week, René Gauthier, second in command of Hydro-Quebec's engineering department in Montreal, told me in January of 1968: "Now we wonder if the reservoir will ever be full—up to elevation 1180. This may happen only once in fifty years." Once again, we found the design engineer planning for the worst. Engineers' mistakes do not always bury them, but it would have been ever so slightly embarrassing had Manic 5's designers mistakenly counted on the reservoir rising to maximum pool and then found themselves with a completed dam and powerhouse and no way of getting water to the turbines.

Besides being deep, Manic 5's intakes had another unusual design twist. Despite their location well below the surface, model tests had shown that because of the flow of the water (it would be turning a corner as it entered the two big tunnels), there was danger of vortex action. "Vortex action" is the whirlpool phenomenon that occurs when the drain is opened in a bath-



Gated intake structures for the two power tunnels near completion just upstream from the dam's east end. The sills of these portals will be 150 feet below maximum water level in Manic 5's reservoir, 170 feet below the crest of the dam.

tub full of water (clockwise in the northern hemisphere, counterclockwise south of the equator).

Vortex action in the intake of a hydroelectric powerhouse introduces air into the system, which not only can cause water hammer, but also reduces the efficiency of the turbines. These huge water wheels, called "runners" by the engineers, are precisely designed machines, and their operation is based on a solid stream of water propelling their blades, not an aerated flow such as the housewife prefers from her kitchen tap.

So Manic 5's designers conceived an unusual intake for the two 36-foot-diameter tunnels. First, to avoid the use of extremely large gates, the intake for each tunnel was divided into two separate portals with vertical-lift gates 36 feet high and 20 feet wide. A 6-foot-thick vertical concrete wall divided the portals, its upstream nose streamlined to improve flow characteristics. The rock outer walls of the portals were lined with concrete that in some places was up to 9 feet thick. Resting on these massive walls and the portal dividers was a huge concrete structure, a kind of face above the actual openings. But this face was mass concrete extending back for 55 feet.

Within this block were the slots in which the 70-ton steel gates would be inserted and ultimately travel up and down when opened and closed.

Just upstream of these gate slots, possibly better described as narrow wells formed in the giant monolith, was another well, extending like the gate wells from the top deck of the intake structure (elevation 1200, the same as the dam's crest) to the roof of the tunnel. This forward well measured 4×14 feet in section and was part of the system designed to break up vortex action. From this well, set 10 feet back from the intake's face, eighteen 3-foot-diameter pipes, spaced roughly 8 feet apart, ran out to the face above each intake gate portal.

The idea here was that water would flow into the tunnel through these holes as well as through the main intake portals. The water entering these ports would join the main stream of water just inside the structure, but hydraulics experts proved with model studies that the flow through the small holes would be just enough to break up a vortex action they said could have been a whirlpool 100 feet deep. So Manic 5's powerhouse intakes were not only impressive for their size, but the seventy-two holes in their faces lent an architectural effect that distracted from the perforated façade's otherwise utilitarian design. At any rate, like so many other components of the project, these intakes would ultimately end up submerged by the waters of the Manicouagan.

This was one of the sad aspects of the project, which I had come to feel was almost a part of me; at least, it was "my dam." And so much of it was going to be lost from view to the visitor of ten years hence. The diversion tunnels and their big gates were already gone; very rapidly the graceful upstream curves of the dam's arches were going underwater, never to be visible again. This massive intake structure, resembling a medieval fortress, was next on the list of disappearing structures. All of Janin's and Evert Ross's underground construction would eventually be full of water so no visitor could ever roam the bowels of the mountain as I had done.

There was a rumor that the road from Baie Comeau was slated to become a major highway, linking the St. Lawrence's north shore with the mining country up north. Tourists and sportsmen could then come to Manicouagan and maybe the construction city would not become a ghost town. Somehow, I hoped this would come to pass. It seemed a shame that Manic 5's spectacular beauty, every bit as impressive as the tallest skyscraper or longest suspension bridge, had to be lost to the lonesome desolation of the bush country.

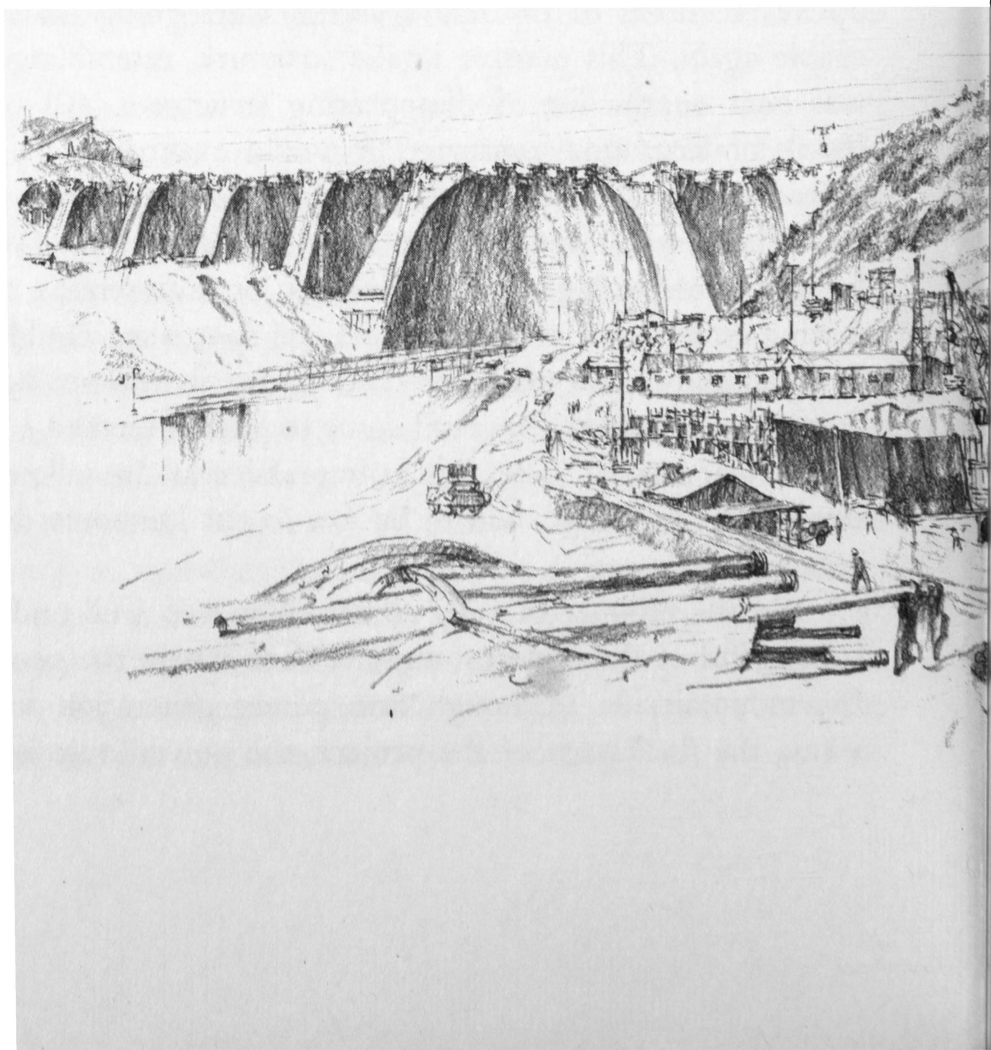
By the summer of 1967 construction was well under way at the downstream end of the underground network where the penstocks emerged from the mountainside. Although first power generation was about three years away, the final stage of the project, the powerhouse itself, had begun. Like

most buildings, Manic 5's powerhouse started out just a hole in the ground. But what a hole! Before Hydro-Quebec's excavation crews were through, they had removed 436,000 cubic yards of earth and rock and had created a rectangular excavation more than 600 feet long, running parallel to the river bank.

They left a rock dike in place directly along the river's bank to protect the excavation from any flow that might be released from the reservoir, since the powerhouse would bottom out well below the riverbed at elevation 620, some 30 feet lower than the base of the dam's main arch (of course, still not as deep as the dam's deepest foundation, the bottom of the deep gorge). This dike's crest elevation was keyed to another consideration—the ultimate level of the headwaters of the Manic 3 dam, still to be built downstream.

The so-called tail-water level, or afterbay, into which a hydroelectric turbine discharges has a direct bearing on the elevation at which the turbine is located in the powerhouse. Manic 5's turbines were placed so they would operate most efficiently in relation to the ultimate level of Manic 3's reservoir, which would create the tail-water pond for Manic 5's powerhouse.

In midsummer of 1967 concreting has begun for powerhouse substructure. At right, final excavation work is nearly complete at southern end of foundation, which had to be blasted out of rock to a depth 580 feet below crest of dam (upper left).



But until Manic 3 was built, the river would still run free, flowing downhill away from Manic 5. So the rock dike, left in place along the river bank in front of Manic 5's powerhouse was designed to create a pond, its water level precisely the same as that of the reservoir to be impounded by Manic 3 in the future.

Behind this dike, though, Hydro-Quebec's crews blasted downward, going deepest about 75 feet in front of the vertical rear wall of the excavation, now encased by a 90-foot-high concrete retaining wall that would ultimately be incorporated into the powerhouse building. At the top of this wall, in another shelf carved into the mountain's rock, a huge rail-mounted, twin gate-leg crane, brought to the project from the completed Manic 2 dam far downstream, was installed to serve the constructors of Manic 5's powerhouse.

The retaining wall, which really defined the rear of the excavation and the rear wall of what would be a 96×616-foot building, was about 350 feet back from the river. The wall was begun in the fall of 1966 and completed with its crane platform in 1967, when powerhouse concreting began in earnest.



To best grasp what was involved here, one must understand the typical turbine-generator set at Manic 5. The term “set” is used because each unit is in fact a set—a turbine—the water wheel, in simple terms—and a generator, a huge cylindrical machine that resembles a mammoth electric motor tipped on its side. Unlike the water wheel at the proverbial old grist mill, the modern turbine is what is called a vertical unit, its drive shaft being vertical instead of horizontal like that of the miller’s wheel.

The water that drives a modern hydroturbine, instead of dribbling off an overhead millrace into flat pans on the wheel, surges through a huge pipe (at Manic 5 the diameters of the penstocks narrowed at the powerhouse to 12 feet) and then enters a spiral-shaped assembly called a “scroll case.” This giant scroll case looks something like a huge snail shell, except that it has a hole through its center. Whereas the snail shell deadends at the center, the scroll case leads the water inward until it comes to the hollow core. The wall of this core has openings which admit the water into it. Within the scroll case’s center is the turbine with its blades. The water flowing at high pressure out of these openings in the center of the scroll case strikes the turbine’s blades causing it to rotate.

The water then falls downward out of the turbine into a mammoth horn-shaped discharge pipe called a “draft tube.” The draft tube curves slightly upward, its neck being vertical and linking directly to the center core of the scroll case and its mouth flaring wider as it directs the water to the tailrace pond. The draft tubes discharge to this pond below the surface, which is why there must be a pond such as was created by the dike at Manic 5.

The rotation imparted to the turbine is then transferred to the generator above it via a huge drive shaft, a steel assembly often 4 or 5 feet in diameter. The generator rotor, attached to this shaft, spins within a stator, which is a stationary ring of electromagnetic coils. As the opposing electromagnetic fields on the rotor and stator react against each other, the huge machine generates electricity.

XVI By the summer of 1967 the dam was nearing completion. There was some talk that the concreters might top it out in this season, but Guy Vachon told me the schedule was very tight. "We could do it, but it will be very close," he said. "The pours are smaller and we're switching to 4-yard buckets. We spend almost the same time on formwork for a pour, but don't put in as much concrete. So production is slower."

One night Gordon Stibbards, of SNC's geology section, was kind enough to agree to a walk across the dam with me. I say "kind" because walking across Manic 5 in July of 1967 was not simply a casual stroll of 4310 feet. Climbing the Matterhorn, I am sure, is tough going, but crossing Le Manic was no picnic either.

We started on the east end where the dam was finished to crest elevation for several hundred feet. I remember being impressed by the fading sunset reflecting on the reservoir's rising waters. I was even more impressed when I glanced at my watch to find it was ten minutes of ten—a long July day to make up for the very short January day. In a way, it was like crossing a bridge with a two-lane concrete roadway and quite high curbs on each side. There were guard rails and drain slots along the curb every so often, designed mainly to drain rain water from the roadway. I wondered if there would ever be wind-blown waves on the huge lake high enough to splash up on the roadway. The design engineers had obviously thought about it because there are many more gutter drains, like the scuppers in a ship's gunwales, than any rainstorm would ever require.

From our vantage point atop the eastern crest, Stibbards and I could see the massive concrete intake structures, really the back sides of them, as they rose closer to crest elevation. These intakes, once the reservoir was at maximum pool, would be island-like structures upstream from the dam, accessible only by a small causeway leading from the dam.

High overhead, but now much closer than they were years back, were the giant 1000-watt, mercury-vapor lamps draped across the valley like a string of gargantuan Christmas lights. They did their job very effectively,

but there was an interesting change from the old days. The highline that carried the lights was originally installed roughly over the dam's axis. But actually, and it was visibly apparent now, the lights were somewhat upstream of the crest, flooding down onto the dark waters. Three or four years before, the lights had been directly over the low lifts in the arches, but as the tilted arches rose, they also angled backward farther downstream. But the big lamps were so powerful it did not matter. You could really read a paper up here now, but Stibbards and I kept walking. We had an obstacle course ahead of us.

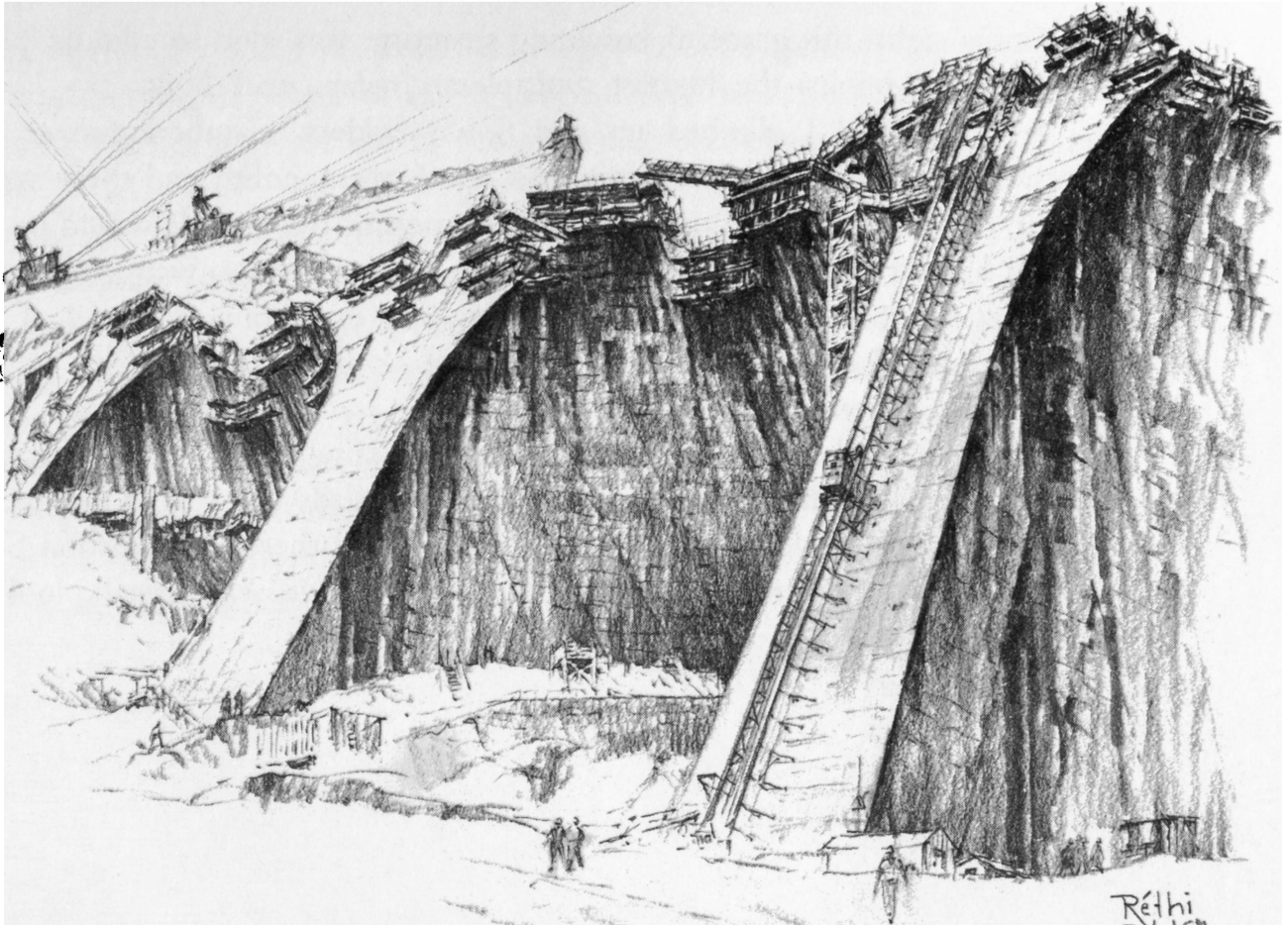
Strolling along on the roadway deck we came upon an incongruity. A portable toilet, painted a sparkling white, was perched on the sidewalk not far from where the roadway ended. Humorous or not, the high-flying outhouses saved many thousands of man-hours at Manic 5. Just like anything else the men working high on the dam needed, these little buildings were brought in on a cableway hook and were never too far behind the concrete crews. When you are working 600 feet up, it is a time-consuming trip to the men's room. So Manic 5's builders brought their men's rooms with them.

Finally we ran out of roadway and came to what was the final pour of each monolith in the dam. Unlike the big mass concrete pours, this lift was heavily reinforced because the roadway cantilevered 6 feet out over the edge both upstream and downstream. Thus the big 1-inch reinforcing bars were imbedded in the concrete to provide tensile strength in the 22-foot-wide roadway deck.

Things had always been crowded in the lifts atop the dam, but now the quarters were really getting cramped. The bullmoose we came upon that night just about fit on the surfaces of the narrow lifts. The main arch is only 16 feet thick at its top and the smaller arches are even thinner. Of course, the gravity crown section, with its vertical upstream face, straddles the arches near the top, so the lifts in between the arches as the dam neared its upper reaches got bigger while the arch lifts themselves reduced in size.

Nevertheless, when you came upon a bullmoose that summer, it inevitably was jammed into a lift with reinforcing bars bent out of the way, sometimes bent flat down against the concrete. The machine's big tires were really unnecessary since it had no room to maneuver anyway. But still the forms had to be raised and the bullmoose came to help. There was also much less room for storage of equipment and other supplies, but Hydro-Quebec solved much of this problem early in the game with precision planning.

For instance, the reinforcing steel required for a specific lift was all cut and bent on the ground, then packaged together and stored until the exact hour that the ironworkers were to work in that lift. This was one of the



Concreters have nearly closed first two arches at west end of dam in July of 1967. The span from buttress to buttress here is 250 feet.

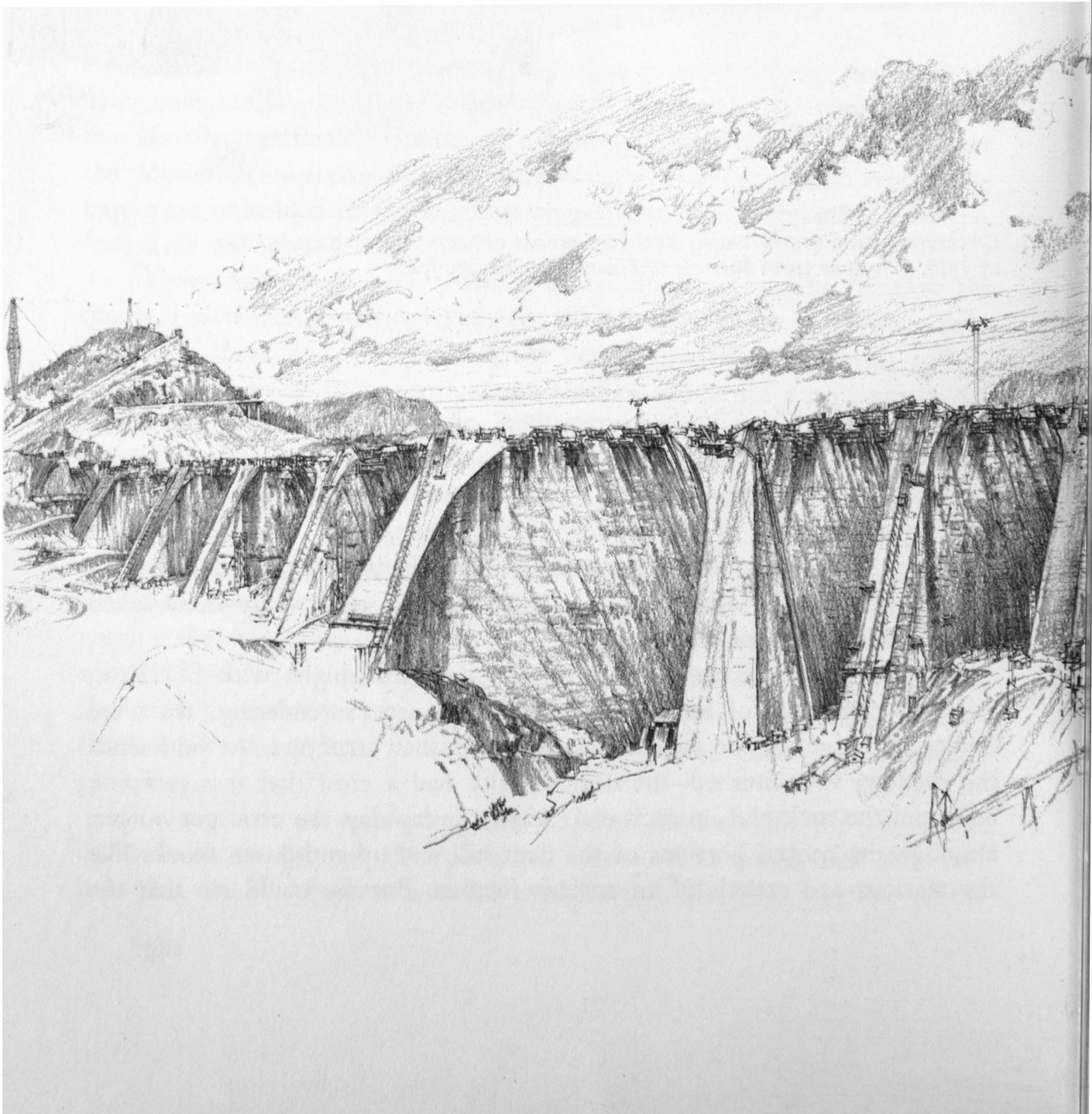
things that gave Manic 5 an atmosphere of non-stop construction. Even during the dinner hours and on Sunday, when the project and the camp was almost like a graveyard, the cableways would often be busy. A few men always seemed to be working during these off hours on what was called “yarding”; placing packages of reinforcing, moving catwalks or bull-moose, all the many odds and ends that could be more easily done when there was no one else around.

There was an excitement up on the dam that night with Stibbards. After all the years of looking at models and artist’s rendering, we were now walking across the top of the almost finished structure. At both ends the roadway was finished—the dam actually had a crest that was creeping out from the rock cliff on each end. Almost every day the crest got longer, although the central portions of the dam still had up-and-down blocks like the merlons and crenels of an ancient fortress. But we could see that the

end was in sight; this graceful, towering structure was soon to take its place in the record books—the highest multiple-arch dam ever built.

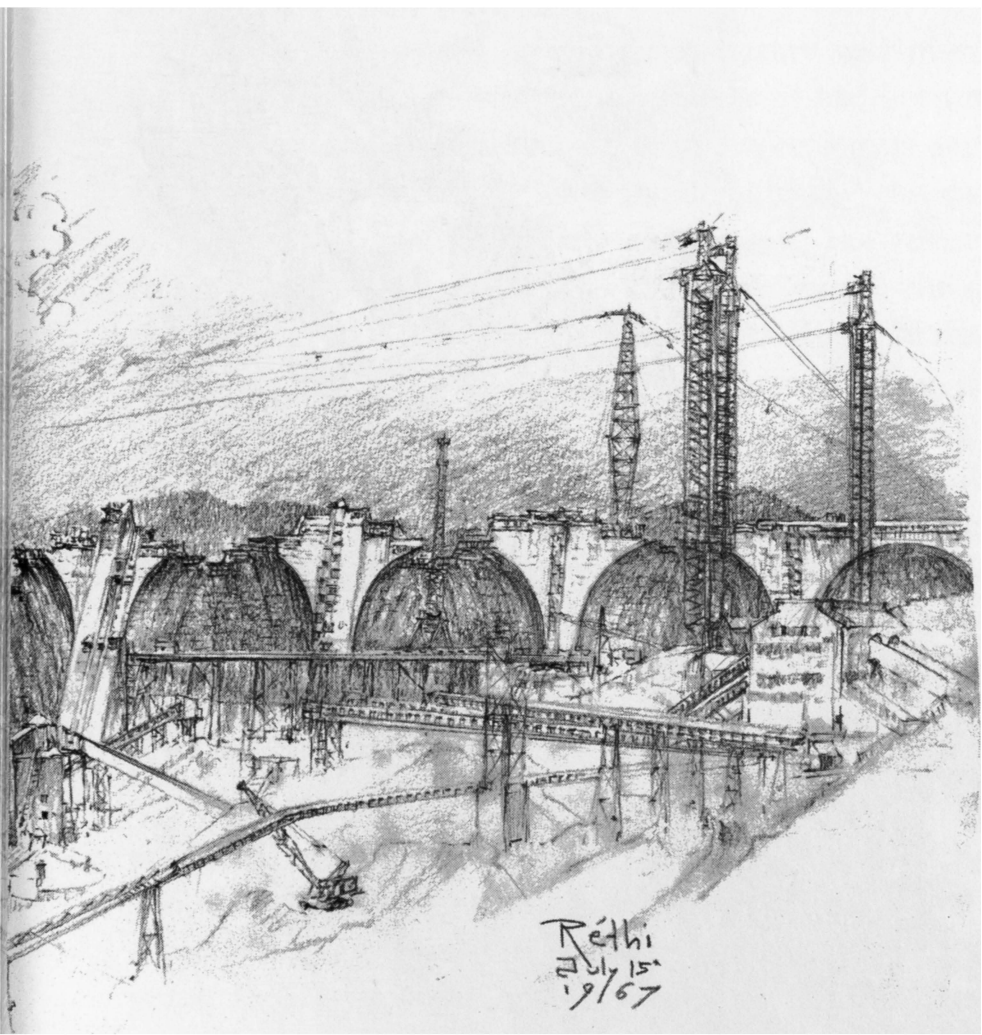
Stibbards and I climbed up and down ladders, clambering over the formwork like monkeys. We came into one high monolith and there was a gallery, piercing back into the completed section of the dam. It would be the last and highest gallery in the dam. Like the crest-riding roadway, with each passing week the tunnels got longer, extending out from each end of the dam. One day, I would be able to walk inside Manic 5 from the cliff on one bank to the other side of the gorge.

The thought was happy and sad at the same time. It was exciting that the dam was finished, but in a way that was really the end of the excitement. One did not want it to be all over. But then there was Gordon Stibbards, a typical construction man in many ways. He was already looking



ahead to the day when he would no longer be a resident of Manicouagan. He was thinking seriously of taking an academic sabbatical—back to school to polish further his expertise in geology, that ever-changing science of the earth.

But as it turned out, Stibbards left Manic 5 and SNC to take a job with the consulting engineers handling the huge Churchill Falls hydro project in Labrador. Next summer would find him back in the boondocks again, helping to build another engineering wonder. One thing about the construction business: one never gets that feeling of being in a rut. Even the men and women who had been at Manic 5 for eight or nine years, a long time in one place by construction standards, would soon be moving on. If they had got bored with this dam, they could look forward to a new and different project in some other location.



Majestic even without its crest, the world's highest multiple-arch dam dwarfs everything in sight including cableway head towers at right that are nearly 400 feet high. Cableway carriage just above central arch is barely able to clear dam, an example of the careful calculations made by engineers years before.

For instance, Churchill Falls had no record-setting dam; it was mostly underground, which entailed blasting a mammoth cavern inside a mountain 1000 feet below the surface. The entire powerhouse would be underground and have a generating capacity of 5.2 million kilowatts, more than four times that of Manic 5. And, interestingly, Stibbards' new project was getting under way because the power-hungry Province of Quebec had signed a contract to buy most of the Churchill Falls electricity.

Big air vents on the face of the main arch well ahead of rising waters; crews take advantage of them while working from floating platforms to spray protective asphalt coating on concrete.



By 1967 one could look out an office window and see the dam. For years it had been a paper dam, thousands upon thousands of engineering drawings. One could not help thinking that the mountains of drawings and the many copies of each produced by the draftsmen, had they been stacked up, might well have formed a big enough mass alone to dam the mighty Manicouagan, a sort of gravity paper dam.

But the dam was there now, a towering concrete monument to engineering, an architectural masterpiece as well. In fact, when I asked about a small sloping setback I had walked up, high on the right buttress, I was told: "It's just an architectural effect." Someone had actually looked at a model or an orthotropic drawing of this massive 700-foot-high concrete structure and, apparently, said: "The thing would look better if we put a little setback running right up along here on the main buttresses." This was hard to believe, but true. I had walked on one of those setbacks that morning and from the ground about a half mile away, you could see the effect. I decided it did add something.

But while I passed on the dam's beauty and most everyone, including the most hard-boiled construction men who had been there since the beginning, commented on what a great structure it was getting to be, Manic 5's designers were beginning what might be called the dam designers' moment of truth. The dam was nearly topped out; the reservoir waters were still rising about 8 inches a week. In so many words, the designers big concern in 1967 was "Will the design work?" As Rock Poulin, the SNC geologist, jocularly put it: "We just hope the damned thing will stand up."

An oversimplification perhaps, but nevertheless, engineers and geologists were watching the dam carefully. And there were many things to watch and monitor. There were the hundreds of drainage holes, drilled from galleries in the dam and its rock foundations, to drain off water that might force its way into the rock as the reservoir waters rose and hydrostatic pressures increased. These holes, 3 inches in diameter and spaced 10 feet apart in a fan-like pattern, had the primary purpose of preventing uplift pressures from developing.

But Jean Larouche's men were using them for another purpose. "Taking advantage of these holes," said Larouche, "flows and pressures are measured and plotted against the rising reservoir." This is done in order to establish a correlation between the geology (the three-dimensional, geologic photograph developed in the early exploratory days), the grouting that was done to the foundation rock, and this seepage data. High pressures and flows in a certain area would indicate that more holes were required. In some cases, more grouting would be required.

That summer, in fact, Gordon Stibbards had grout crews hard at work

in the very bowels of the dam, deep down in the gorge where it had been plugged with concrete, beneath the main arch. Heavy flows of water and high pressures had been pinpointed to a horizontal seam, a construction joint in the mass concrete plug that had washed out for some reason and was now channeling water into the drainage system at an unacceptable rate. Stibbards' job: stop these flows or, at least, reduce them to an acceptable rate.

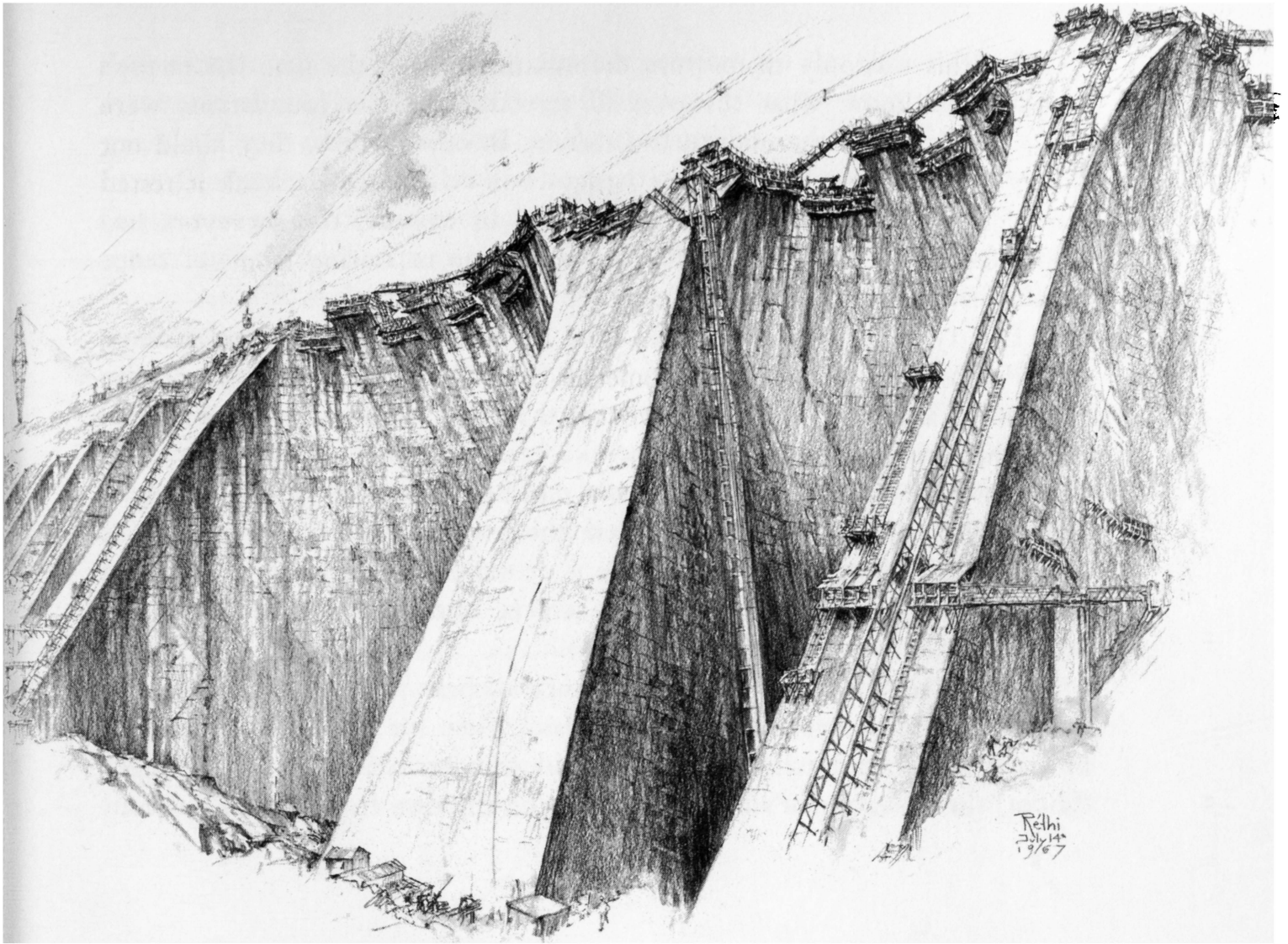
After considerable drilling of grout holes and observation drainage holes, this "leak," if you will, was plugged. Stibbards' success was in a way reassuring. They had coped with a trouble spot at nearly the lowest point in the dam's foundation, where pressures were as high as any at the time. Granted, when the reservoir was full, pressures would be even greater. The operating head would be 506 feet. Pressures under the main arch, where concrete extended 703 feet below the dam's crest, could be even greater.

Besides observing the water flows and pressures in the drainage curtain of the dam's foundations, engineers also monitored drainage in the arches of the dam itself. This is where the so-called face drains, the holes formed in concrete about 10 feet back from the face and spaced about 8 to 10 feet apart, played their role. Any leakage through the concrete theoretically would find its way to these drains that were 6 inches in diameter in the small arches, 12 inches in the main arch. The face drains connected with the galleries that ran horizontally through the dam at about 100-foot vertical intervals.

"Observations from these drains," explained Larouche, "provide a good indication of the quality of the concrete and the workmanship. They also dictate when and where remedial measures must be taken." These remedial measures either involved drilling and grouting or, possibly, simply regrouting in one of the vertical construction joints with its permanently embedded grout system.

One of the most fascinating systems of instrumentation at Manic 5 was the giant plumb lines used to measure horizontal deformation. Keeping in mind how a brick mason uses his plumb line, imagine a huge version thereof suspended on a piano wire some 200 feet long. These were called "pendulums" at Manic 5. They were installed in vertical wells formed in the dam. Because a single wire 600 or 700 feet long would resonate too much, precluding accurate measurements, a pendulum system, extending from the top of the dam to the foundation, was comprised of four plumb lines.

These wells intersected the galleries in the dam (actually they ran immediately next to the galleries) so that measurements could be taken every 100 feet vertically. At these reading stations inside the dam, the position of the wire in relation to the dam was measured by viewing the wire with a microscope mounted on a micrometer slide.



Shadows highlight Manic 5's dramatic architecture, graceful lines molded in massive concrete. The highest monoliths in the central arch at left are more than 600 feet above lowest point in the dam's foundation.

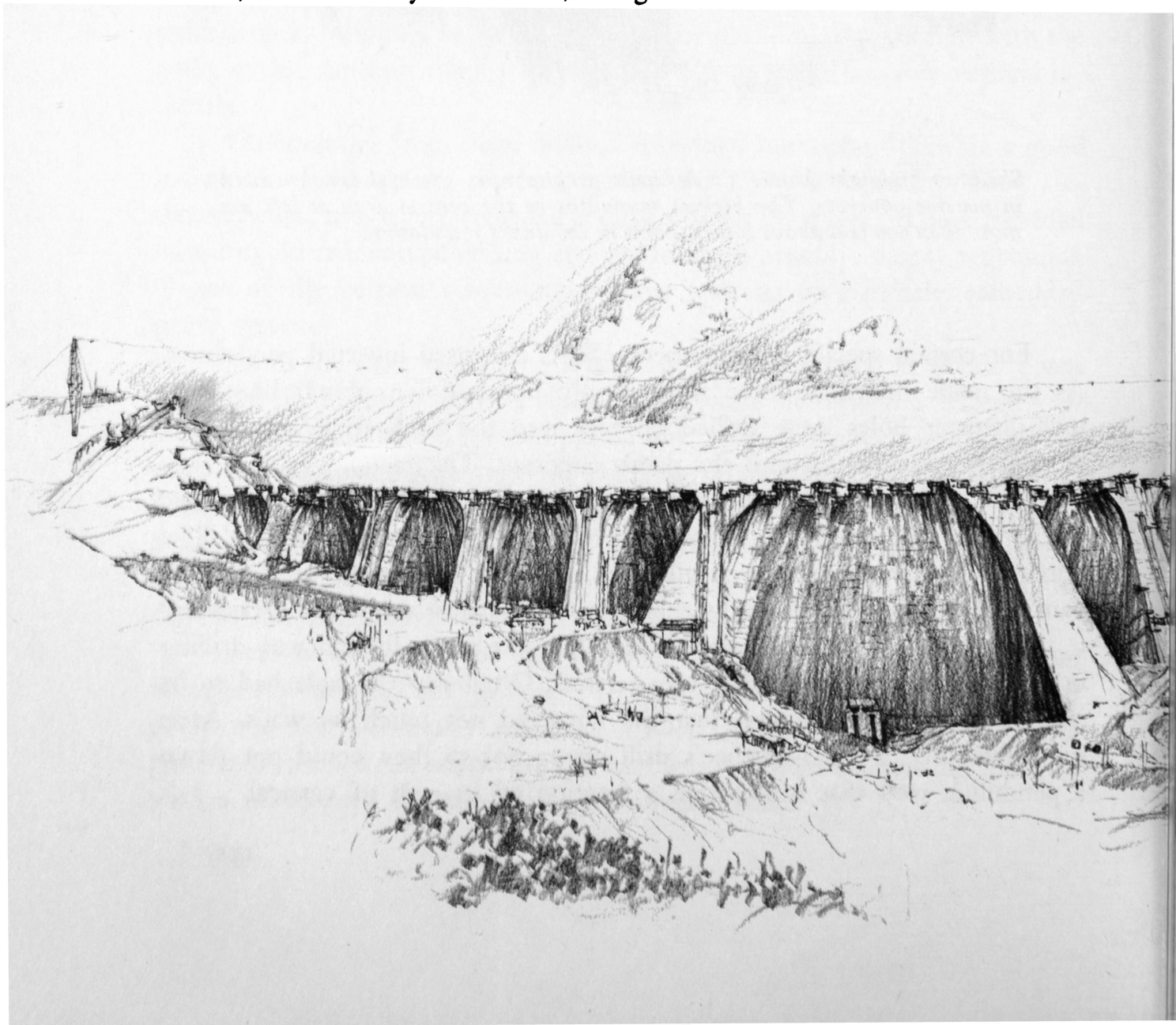
For certain specific measurements, SNC also used inverted pendulums. As the name indicates, these were simply upside-down plumb lines. Six-inch-diameter holes were drilled 90 feet into the rock foundation, then, of course, extended up into the dam's concrete. The piano wire was then anchored with grout in the rock at the bottom of the hole. The other end of the wire was attached to a float in a tank at the top reading station. The wire would remain vertical at all times, but any movement of either the dam or the rock foundation could be measured against the wire's verticality.

One of the toughest parts of installing these pendulums was drilling in the rock a 6-inch hole that was vertical. Obviously the hole had to be straight and vertical enough that the wire did not touch its walls. After some difficulty, Hydro-Quebec's drill crews got so they could put down a pendulum well that was within a fraction of an inch of vertical.

But this was only to measure deformation within the dam. Larouche's men had to know what the over-all structure and its foundations were doing in relation to the undisturbed terrain. In other words, they could not simply measure movements of the structure in relation to the rock it rested on since the rock itself would also move. In essence, the surveyors had to get far enough away from the dam and begin measuring from reference points that theoretically were stable.

This type of measurement is done by means of simple triangulation, based on a relatively easy trigonometric calculation. To locate the precise position of a given point, the surveyors take sights from two known locations through theodolites, telescope-like precision instruments. The space between these two points is a precisely measured distance. With two angles and one leg of the triangle established, the length of the other two legs is found and the apex of the third angle is determined. At Manic 5, this third point was always one of some eighty targets, metal plates embedded in the arches and buttresses of the dam.

But surveyors do not simply rely on two base points in measuring the deformation of a huge structure like a dam. They use an elaborate network of triangulation points so they can double- and triple-check. They might "shoot," in the surveyor's lexicon, a target on the dam from several different



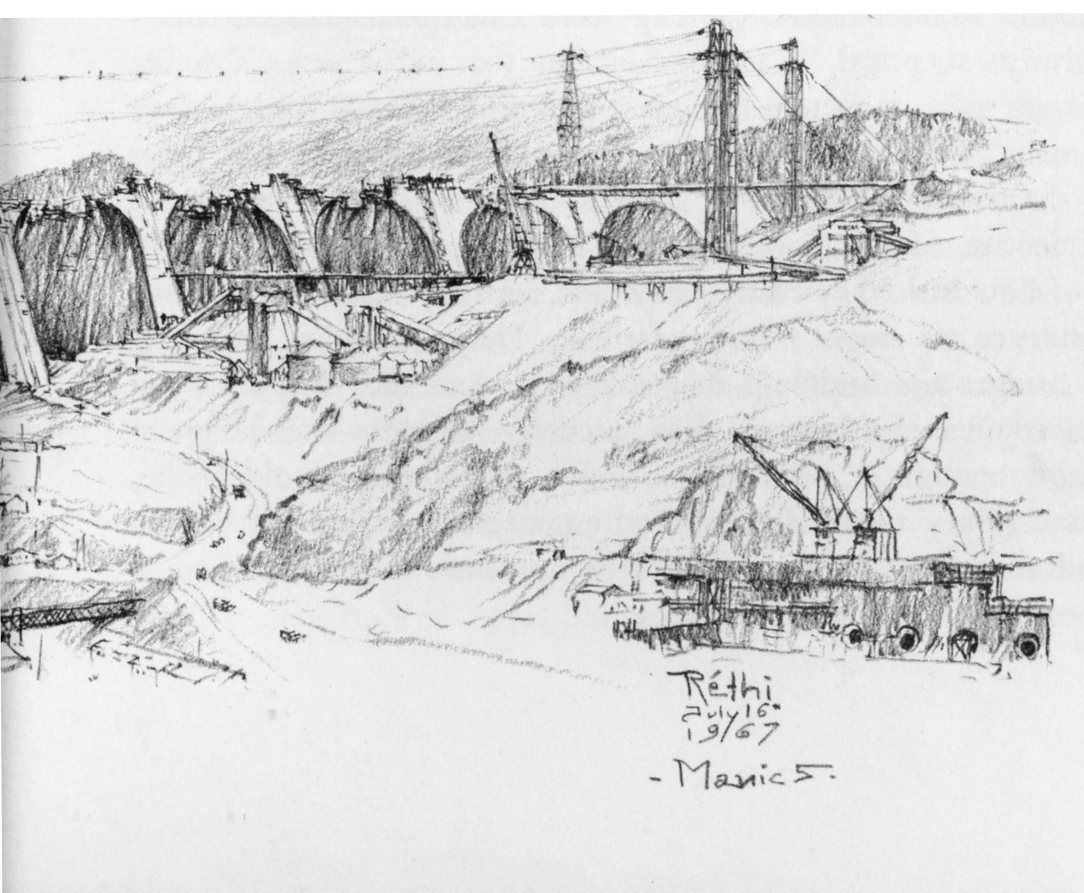
sets of base points. At Manic 5 there were thirteen theodolite piers in the network, all within about 700 feet of the dam, plus two back-target sighting piers, located 2000 feet from the dam.

When dealing with such a huge structure, it is important to be able constantly to check and recheck all the reference points used in the calculations. The theodolite piers at Manic 5 were big concrete piers founded in rock, but still, if the rock moved, the pier would also, and the triangulation would be meaningless.

So, just as the pendulums installed in the dam were used to measure horizontal movement of the dam, more pendulums were used to determine movement of the theodolite piers. Five inverted plumb lines, anchored 60 feet into rock, were incorporated into the triangulation network to help establish precisely the location of the so-called fixed reference points in the system.

To check the position of the eighty targets on the dam, surveyors started by measuring two so-called base lines. These are the backbone of the entire triangulation network upon which all measurements are based. One is 400 feet long, the other 500 feet. The plumb lines were then checked to see that these particular piers had not moved. Then they began the elaborate system of cross-triangulation to establish the exact position of all the

Thirteen arches vault across the Manicouagan Valley, spanning 4310 feet between abutments. The powerhouse, shaping up at lower right, is about half a mile downstream from the dam.



theodolite piers in relation to each other. As an example of the pains taken to get exact measurements (within $\frac{1}{25}$ of an inch), all this work was done at night when there were no heat waves in the air to distort vision and temperature conditions were more uniform. The targets were illuminated for the night-owl surveyors.

Once the positions of the piers in the triangulation network were established and verified, the engineers could then train their sights on the targets on the dam itself. All these measurements were then fed into the computer back in Montreal and the exact horizontal location of each target on the dam was determined.

Vertical deformation was measured by very precise leveling, again using delicate surveying instruments. The leveling began at a bench mark 6000 feet from the dam, a point considered to be stable, and involved checking the elevation of an elaborate circuit of check points on both sides of the river. This leveling method is used to check vertical deformation of both the rock foundation and the structure itself. The same targets embedded in the dam were used for these vertical measurements. By the summer of 1967 the geologists who had said the rock foundation was good had been proved correct. There had been no movement, but ultimately there would be some, however slight. If anything moved more than $\frac{1}{25}$ of an inch, it would be detected.

The results of these deformation measurements were cross-checked and correlated with the readings logged from the stress-measuring instruments embedded in the dam. The deformation measurements were also checked against computed figures. Once again, the design engineer checked his calculations against the real thing, asking those questions we laymen find a bit hard to cope with: Will it work? Will the dam withstand the forces as the computer and slide rules said it would?

One sometimes wonders about the engineer's traditional manner, somewhat hedgy, always skeptical, forever suspicious that what was "absolute truth" might prove to be not quite the case. My father always used to say: "The smartest man is the one who realizes how little he knows and there is nothing like the confidence borne of crass ignorance." The engineer, the geologist, the scientist, all of whom appear to know so much, are obviously gravely aware of how little they really know and for this reason do not have the divine confidence we might expect of them. They remember the dams that failed, the bridges and buildings that collapsed. And they know all too well how these engineering failures often occurred—because the designers just did not know enough or assumed too much. It may be an old cliché, but the doctors do bury their mistakes, and engineers' mistakes very often bury *them*—and sometimes thousands of other persons. The responsibility is heavy and was ever-present at Manic 5.

XVII During the decade it took to build Manic 5, most attention focused on the dam. The electricity that Manic 5 and its sister projects on the Manicouagan and Outardes rivers would produce was mostly taken for granted. Like many things not completely understood, electric power is matter-of-factly accepted by mankind. After all, you cannot even see it. You just turn on a switch and there it is. It just comes out of the wire. The one thing most every one knows about electricity is that it can kill you: "Keep your finger out of the light socket."

The concrete and steel of the dam is tangible. You can see it and appreciate that it is a fantastic accomplishment of men. It stores water and forms a huge lake that is very visible. And this stored water is used to turn water wheels of some kind and they make electricity. Then what happens? Well, you hook a wire to the machine, string the wire on poles or towers to wherever you want this electricity, and the power comes out of the other end of the wire. Sounds simple enough. But it isn't.

At the risk of oversimplifying what most text books devote chapters to, the wire in question can be compared to a water pipe. This electrical pipe is referred to as a conductor. Like the water pipe, the physical size of the electrical conductor has a direct bearing on how much electricity it can conduct.

Hydro-Quebec engineers were faced with moving the Manic-Outardes complex's 5.5 million kilowatts of power to Quebec's population and industrial centers hundreds of miles away in the St. Lawrence Valley between Quebec City and Montreal. They were talking in terms of a potential annual production of a startling 30 billion kilowatt-hours. They would either have to use very large conductors or a great many conventional-sized conductors if they stayed with conventional voltages—which can be loosely considered the equivalent of the pressure supplied to force water through a pipeline.

With high-tension transmission line voltages pretty well standardized in North America at 115,000 volts, the Canadians had not been afraid to pioneer way back in 1932, building a 220,000-volt, 300-mile-long line from

the Beauharnois generating station in southwest Quebec to Toronto. And in 1956 Hydro-Quebec was again at the vanguard, putting into operation a 310,000-volt system to deliver Bersimis power to Montreal 380 miles away.

But if they used the Bersimis voltage to move the huge Manic-Outardes block of kilowatts, they would need twenty transmission lines, a solution that was obviously out of the question. At the time the early planning was under way for Manic-Outardes, the Soviet Union had already gone to 525,000 volts, coping with the same type of problem the Quebecois faced. The Russians were developing the mammoth hydroelectric potential of Siberia and had to move power hundreds, even thousands of miles to load centers west of the Urals.

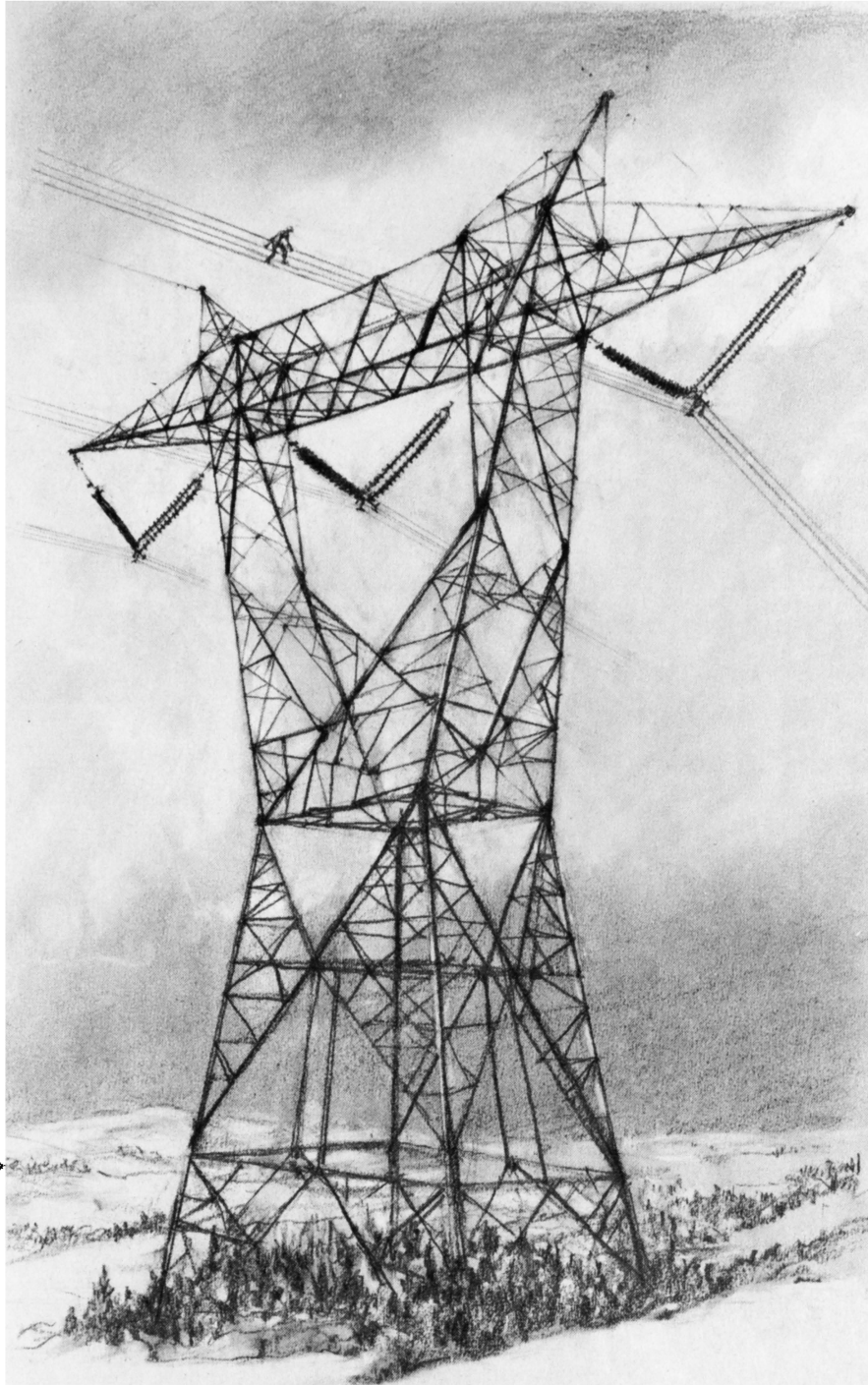
While the 525,000-volt system was feasible (several United States utilities had 500,000-volt systems on the drawing boards and so-called extra-high voltage—more than 345,000 volts—was coming into world-wide vogue), the forward thinkers at Hydro-Quebec wanted a system that could handle even more than Manic-Outardes. What of the mighty rivers flowing into James Bay to the north? What of Churchill Falls (at that time still in the talking stage)?

It was in August of 1962 that Hydro-Quebec decided to bring the power generated at Manic 5 to Montreal via an unprecedented 735,000-volt transmission system. While solving one problem—only three lines would be needed—the use of such high voltage presented many other unsolved problems since the Canadians were once again pioneering.

To start, the three phases of each circuit (alternating-current transmission circuits involve three wires called “phases”) had to be suspended on the towers so that there was 50 feet of space between each phase. Furthermore, the conductors had to be kept at least 40 feet from the ground at all points along the line. This meant that engineers had to design special towers for the lines.

Theoretically a three-phase circuit to handle 735,000 volts would require conductors 4½ inches in diameter, a somewhat unwieldy size of wire, to say the least. Stringing such monster cables would be impracticable, if not impossible. So Hydro-Quebec engineers decided on bundled conductors, not a new idea, but never before done on this scale. A bundled conductor would involve four 1.38-inch conductors for each phase, kept 18 inches from each other and connected electrically by aluminum castings called “damper spacers.” These damper spacers are placed about 200 feet apart.

Although the bundles of smaller conductors would be somewhat easier to manage, their use did involve stringing four cables simultaneously, and each circuit would require twelve conductors. To build the complete system with its three main circuits and three tielines along the way, Hydro-Quebec line crews would string more than 14,000 miles of conductor.



Thousands of huge towers like this support record-setting 735,000-volt transmission lines that deliver Manic 5's huge block of power to Quebec City and Montreal.

The basic system begins at two big collector stations, placed about 40 miles apart between the Manicouagan and Outardes rivers. One of these is at Micoua, about halfway up the road to Manic 5. The other is near the Manic 2 dam, about 17 miles north of Baie Comeau, and receives power from the southern stations—Manic 1, Manic 2, Outardes 3, and Outardes 2—via 315,000-volt circuits. At this Manicouagan collector station, giant transformers step up the voltage to 735,000 volts, then it travels 230 miles to a



Workers dismantling crane trestle in foreground signal the close-at-hand completion due in 1968, but overhead the concrete buckets continue the airborne delivery.

substation near Quebec City, crossing the St. Lawrence River near that city. This 735,000-volt line (actually there are two parallel lines following this route) then runs another 135 miles to a substation at Boucherville near Montreal.

A third transmission line is entirely on the north bank of the St. Lawrence, beginning at Micoua, the station that handles Manic 5's power output, and running 245 miles to the Laurentides substation near Quebec City. This first leg went into operation in 1970 with the final link of the third line, a 158-mile section from Laurentides to Duvernay substation near Montreal, set to operate in 1971.

The project was an enormous challenge and there was not much time. The first line had to be completed by 1965 to handle the more than 1 million-kilowatt block of power from Manic 2; the enlarged Manic 1 plant was to follow with more kilowatts. By 1969 Outardes 3 and 4 had come on line and finally, in 1970, the granddaddy put its huge reservoir to work—Manic 5's first turbine began to turn in August, 1970, and power surged the greatest distance of all, nearly 500 miles to Montreal.

Montrealers, who had never seen Manic 5—except possibly via a spectacular closed-circuit color television hookup linking the project with Expo 67—were now using electricity made deep in the north country. And, as usual, most would never give it a thought. Few would think of the thousands of men who had labored against the freezing winds of the Manicouagan gorge, blasting through the granite rock, risking their lives high on the dam, to make sure that light glowed brightly at the flick of a switch.

The men who built the transmission lines were no less heroes either. From the electrical engineers and technicians from Canada, Sweden, France, and the U.S., who co-operated to make the 735,000-volt lines technically possible, to the loggers and towermen who cleared the rights-of-way and erected the huge steel towers, they were all pioneers. The dams and the powerhouses of the Manic-Outardes complex, certainly a monument to engineering, would have all been for naught if the extra-high-voltage transmission lines could not have been built. But the men of Hydro-Quebec had done both.

With two of the three transmission lines completed and in operation in the summer of 1968, construction was still continuing at Manic 5. The dam itself was complete with the exception of 1 cubic yard, a ceremonial bucket of concrete that was to be poured by the Premier of Quebec as part of a gala celebration. The actual "opening," as Hydro-Quebec called it, had been delayed because of the ill health of Premier Daniel Johnson, but the date was finally set for September 26.

A few weeks prior to this there had been a moment of exasperation. One morning someone looked up at the towering structure, scanning its crest

to a tiny spot near the center of the main arch. Here a small portion of the roadway's sidewalk had been left unfinished the day before. This was to receive the final bucket of concrete. But this late-summer morning it was discovered that somehow, through some colossal blunder during the night, the final yard had been poured. The gray concrete edge along the downstream side of the crest was complete.

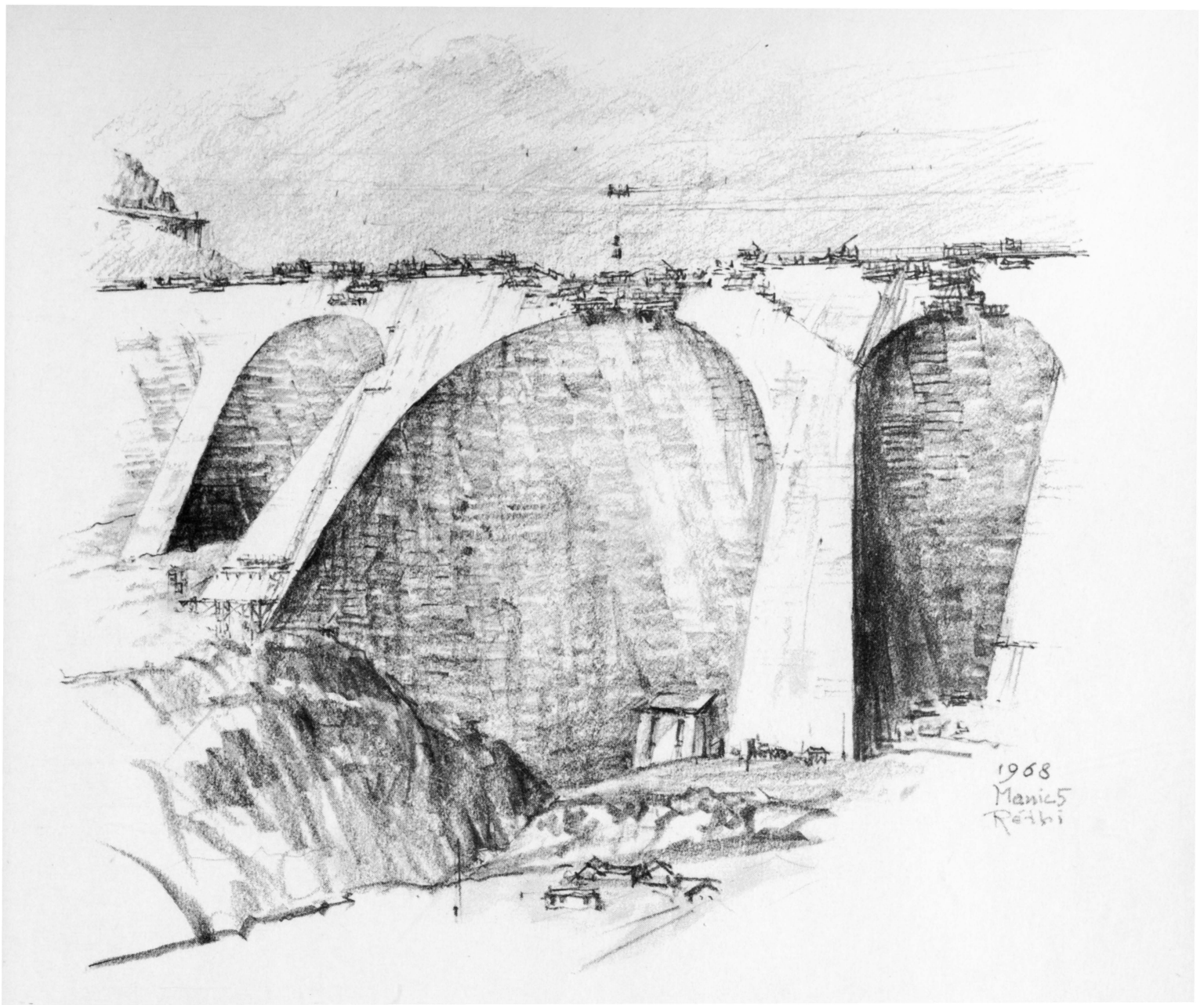
The consternation in Guy Vachon's office that morning cannot be described. It was impossible! Who could have done such a thing? Well, no one had. On close inspection atop the dam, it was discovered that the "concrete" that had been placed was hollow. In fact, it was not concrete at all. Pranksters had filled in the space with wood panels, then plastered over the wood with mortar. There was still a pour for the Premier.

But, ironically, that final cubic yard of concrete might better have been poured. Premier Daniel Johnson never lived to perform the ritual. He came to Manic 5 on September 25 to host a grand party. Late into the night the Premier shook the hands of hundreds of dignitaries, telling all how proud he was of Quebec, La Belle Province. Not only was Quebec beautiful, but it had built the world's highest multiple-arch dam. This was the first time Mr. Johnson had seen the pride of Quebec and he seemed as awed as the rest of us.

That night Premier Daniel Johnson died in his sleep in the guest house at Manic 5. Today the dam is called the "Daniel Johnson Dam." The project is still Manic 5, but the dam itself was renamed in his memory.

But the project was not yet finished. I toured the site that sad day. All work was suspended, of course, and there was an eerie silence as there always had been on Sundays. One thing that continued as it had for the last five years was the ever-rising waters of the reservoir. Despite the now vast surface area of the mammoth lake, the level was still increasing at about 1 ½ inches each day. It had reached elevation 1076 by that day in September, slightly more than 100 feet from maximum operating level, 1180 feet.

But there was still much to be done. Work had not started on the big steel surge tanks that would stand high on the slope above the powerhouse. They would be 80 feet in diameter and 175 feet high. The cableway towers were still in place but daredevil steelworkers were due to begin dismantling them soon. The big aggregate piles that fed the concrete plant were all but gone now; the plant still standing forlornly and turning out concrete for the powerhouse. But one of its big cement silos was being taken down. The cement trucks that had roared up the road from Baie Comeau almost continuously for all these years were now few and far between. There was only the powerhouse, and the large pours there, those in its substructure around the embedded parts of the turbines, were already in place. The powerhouse superstructure, in fact, was completed by the end of the 1968 construction



Midsummer 1968 brings concrete crews together at the center of the main arch. The gap is closed in August of that year and in September Manic 5 is officially “opened.”

season and the installation of the eight big turbines and generators started in the spring of 1969.

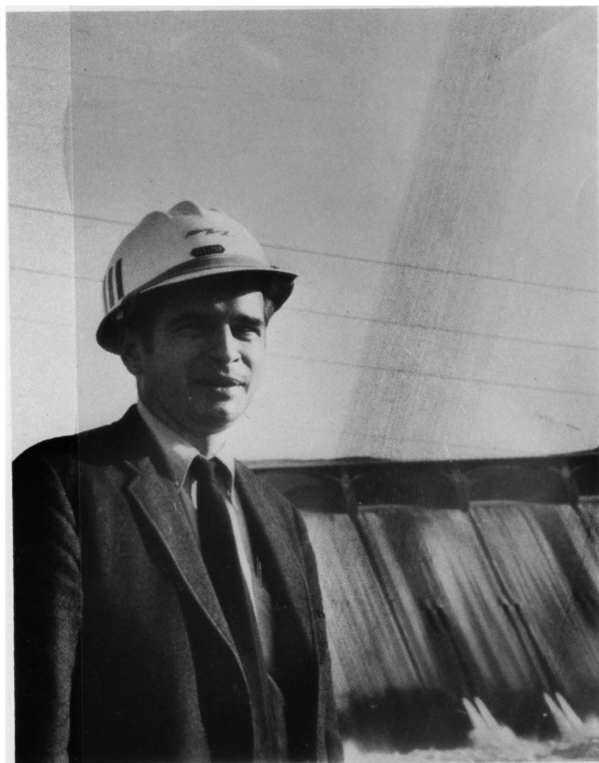
Basically the powerhouse is just that, a house for the power generating units. The walls of the building have one other job in addition to supporting the roof: they support giant rail-mounted cranes which lift the huge components—a 159-inch-diameter water wheel called a “runner” that weighs about 50 tons, a mammoth drive shaft linking the turbine to the 325-ton generator rotor. When all eight of these began to rotate 180 times each minute the project was officially done.

But for me it was that final cryptic entry in my notebook: “Fleur-de-lis on lookout at half mast. D. Johnson dead 9/26/68.” Manic 5 was done. A monument had become a memorial.

(continued from front flap)

neering feats.

The result is a book filled with the excitement of construction—the noise, the movement of men and machines, and the working out of a dream whose reality is the eventual production of untold millions of kilowatt hours of electricity annually for Canada and America—in all its phases from the first wilderness surveys in 1959 to the final installation of the big generators and turbines ten years later.



William W. Jacobus, Jr. is a senior editor of *Engineering News-Record* where he spends his time researching and writing about feats of engineering for both professionals and laymen.

JACKET TYPOGRAPHY BY RALLOU MALLIARAKIS

Printed in the U.S.A.



Lili Réthi was an artist who used her talents “mainly to portray engineering and architectural achievements,” said an article in *Engineering News-Record* a few years ago. “Miss Réthi’s pictures hang in the offices of many of the country’s biggest and best known manufacturing and construction companies. As far back as 1941, only two years after she came to the U.S., 100 of her pictures were exhibited by the Architectural League in New York. In the same year, another 100 were featured prominently at the annual meeting of the American Society of Civil Engineers. In 1944, another 40 pictures were exhibited at the Metropolitan Museum of Art in New York City.” Miss Réthi illustrated several books and recorded the progress of some of the biggest construction jobs in Europe and America—including New York’s huge World Trade Center.

It is sad to record that Lili Réthi died shortly after completing her Manic 5 drawings. Their publication here stands as a memorial to this tiny lady’s great talent and indomitable spirit.